

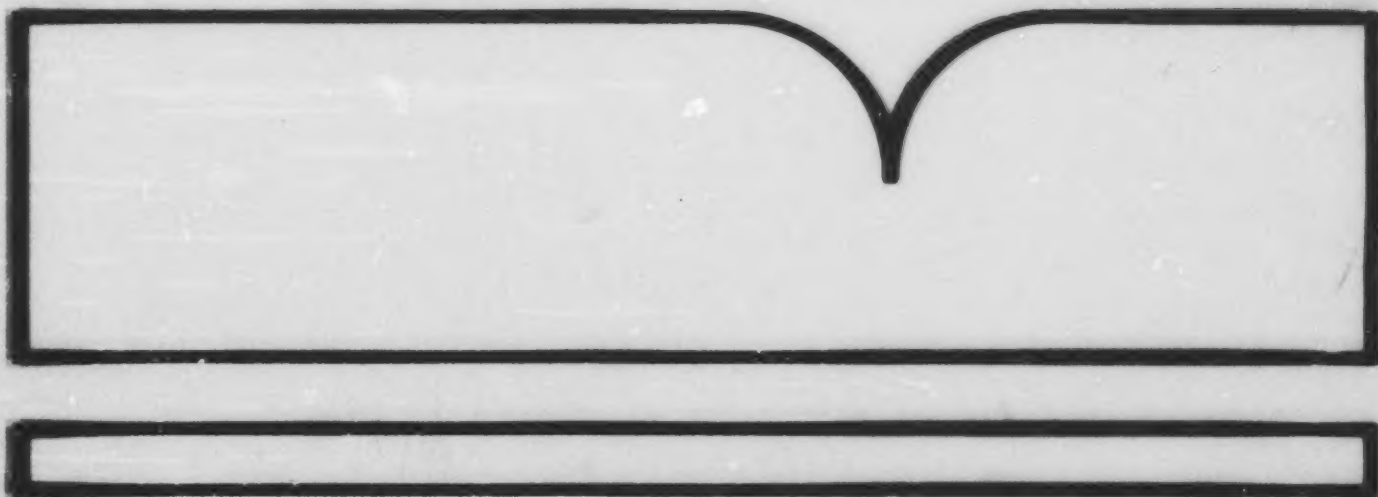
Disposal of Spent Sorbent from Dry FGD
(Flue Gas Desulfurization) Processes

Battelle Columbus Labs., OH

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Feb 83



BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

EPA-600/7-83-009

February 1983

PB83-165266

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

DISPOSAL OF SPENT SORBENT FROM
DRY FGD PROCESSES

by

P. M. Stephan, H. S. Rosenberg, and R. B. Bennett
Battelle's Columbus Laboratories
Columbus, Ohio 43201

Under Subcontract to
Buell Emission Control Division
Envirotech Corporation
Project Monitor: William T. Langan

Contract No. 68-02-3119

Project Officer

Theodore G. Brna
Utilities and Industrial Power Division
Industrial Environmental Research Laboratory
Research Triangle Park, North Carolina 27711

OFFICE OF ENVIRONMENTAL ENGINEERING AND TECHNOLOGY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

EPA-287 (Cir.)
(4-78)

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)			
1. REPORT NO. EPA-600/7-83-009		3. RECIPIENT'S ACCESSION NO. PB83-165266	
4. TITLE AND SUBTITLE Disposal of Spent Sorbent from Dry FGD Processes		5. REPORT DATE February 1983	
		6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) P. M. Stephen, H. S. Rosenberg, and R. B. Bennett (Battelle Columbus Laboratories, Columbus, OH)		8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Buell Emission Control Division* Envirotech Corporation 200 North Seventh Street Lebanon, Pennsylvania 17042		10. PROGRAM ELEMENT NO.	
		11. CONTRACT/GRANT NO. 68-02-3119	
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 10/79 - 1/81	
		14. SPONSORING AGENCY CODE EPA/600/13	
15. SUPPLEMENTARY NOTES IERL-RTP project officer is Theodore G. Brna, Mail Drop 61, 919/541-2683. (*) Now General Electric Environmental Services, Inc.			
16. ABSTRACT The report gives results of a study of sintering and leaching mechanisms of fly ash/spent sodium sorbent mixtures from a dry injection flue gas desulfurization (FGD) process. It includes an estimate of the economics of pelletizing and sintering to handle the fly ash and spent sorbent from a 500 MW power plant burning low sulfur western coal using a dry injection FGD process. The process includes dual disc pelletizing circuits and a furnace with an output of nearly 717 tonnes/day of pellets sintered to a temperature of 950-1000 C. In laboratory tests, pellets with fly ash and either spent nahcolite or spent trona (both reacted with SO ₂), when thermally treated at 1000 C and mildly stirred in water for 100 hrs, lost 30-60 percent of the total sulfur in the pellets as SO ₂ evolved or SO ₄ leached. Under similar conditions, 3-15 percent of the available sodium leached. Encapsulating the dried pellets (or pellets fired at 925 C in concrete or asphalt mixes) did not significantly inhibit the leaching in water of the soluble alkaline sulfates from the pellets. Cured concrete and asphalt samples containing pellets on a 20-percent-by-volume substitution for limestone aggregate exhibited losses in compressive strength of 50 and 75 percent, respectively. Estimated capital cost is \$40.55/kW. The levelized annual revenue requirement is nearly 4.92 mills/kWh.			
17. KEY WORDS AND DOCUMENT ANALYSIS			
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pelletizing	Pollution Control	13B
Flue Gases	Fly Ash	Stationary Sources	21B
Desulfurization	Sodium	Dry Injection Process	07A, 07D 07B
Coal	Sorbents		21D 11G
Sintering	Economics		13H 05C
Leaching	Calcium Carbonates		
18. DISTRIBUTION STATEMENT Release to Public		19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 61
		20. SECURITY CLASS (This page) Unclassified	22. PRICE

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)			
1. REPORT NO. EPA-600/7-83-009		3. RECIPIENT'S ACCESSION NO. PB83-165266	
4. TITLE AND SUBTITLE Disposal of Spent Sorbent from Dry FGD Processes		5. REPORT DATE February 1983	
		6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) P. M. Stephen, H. S. Rosenberg, and R. B. Bennett (Battelle Columbus Laboratories, Columbus, OH)		8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Buell Emission Control Division* Envirotech Corporation 200 North Seventh Street Lebanon, Pennsylvania 17042		10. PROGRAM ELEMENT NO.	
		11. CONTRACT/GRANT NO. 68-02-3119	
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 10/79 - 1/81	
		14. SPONSORING AGENCY CODE EPA/600/13	
15. SUPPLEMENTARY NOTES IERL-RTP project officer is Theodore G. Brna, Mail Drop 61, 919/541-2683. (*) Now General Electric Environmental Services, Inc.			
16. ABSTRACT The report gives results of a study of sintering and leaching mechanisms of fly ash/spent sodium sorbent mixtures from a dry injection flue gas desulfurization (FGD) process. It includes an estimate of the economics of pelletizing and sintering to handle the fly ash and spent sorbent from a 500 MW power plant burning low sulfur western coal using a dry injection FGD process. The process includes dual disc pelletizing circuits and a furnace with an output of nearly 717 tonnes/day of pellets sintered to a temperature of 950-1000 C. In laboratory tests, pellets with fly ash and either spent nahcolite or spent trona (both reacted with SO ₂), when thermally treated at 1000 C and mildly stirred in water for 100 hrs, lost 30-60 percent of the total sulfur in the pellets as SO ₂ evolved or SO ₄ leached. Under similar conditions, 3-15 percent of the available sodium leached. Encapsulating the dried pellets (or pellets fired at 925 C in concrete or asphalt mixes) did not significantly inhibit the leaching in water of the soluble alkaline sulfates from the pellets. Cured concrete and asphalt samples containing pellets on a 20-percent-by-volume substitution for limestone aggregate exhibited losses in compressive strength of 50 and 75 percent, respectively. Estimated capital cost is \$40.55/kW. The levelized annual revenue requirement is nearly 4.92 mills/kWh.			
17. KEY WORDS AND DOCUMENT ANALYSIS			
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pelletizing	Pollution Control	13B
Flue Gases	Fly Ash	Stationary Sources	21B
Desulfurization	Sodium	Dry Injection Process	07A, 07D 07B
Coal	Sorbents		21D 11G
Sintering	Economics		13H 05C
Leaching	Calcium Carbonates		
18. DISTRIBUTION STATEMENT Release to Public		19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 81
		20. SECURITY CLASS (This page) Unclassified	22. PRICE

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTION
HERE

ABSTRACT

The objectives of this research program were to study the sintering and leaching mechanisms of fly ash/spent sodium sorbent mixtures from a dry injection dry flue gas desulfurization (FGD) process, and to determine the economics for a pelletizing and sintering facility for processing these wastes.

A conceptual process flow diagram and equipment description have been prepared for a facility which would process and somewhat stabilize alkaline fly ash/spent sorbent mixtures from a dry flue gas desulfurization (FGD) system for a 500 MW power plant burning low sulfur western coal. The process includes dual disc pelletizing circuits and a traveling grate furnace with an output of nearly 717 tonne per day of pellets sintered to a temperature between 950 C and 1000 C.

In laboratory tests, pellets containing fly ash and either spent nahcolite or spent trona (both reacted with SO_2), when thermally treated at 1000 C and mildly stirred in water for 100 hours, lost from 30 percent to 60 percent of the total sulfur in the pellets as SO_2 evolved or SO_4 leached. The amount of sodium leached under similar conditions ranged from 3 to 15 percent of the amount available.

The encapsulation of dried pellets or pellets fired at 925 C in concrete or asphalt mixes did not significantly inhibit the leaching in water of the soluble alkaline sulfates from the pellets. In compressive strength tests, cured concrete samples and asphalt samples containing pellets on a 20-percent-by-volume substitution for limestone aggregate exhibited losses in strength of 50 percent and 75 percent, respectively.

The cost estimates for a dry FGD by-product stabilization facility for a 500 MW power plant are nearly \$20 million in total capital required, or \$40.55 per kilowatt. The levelized annual revenue requirements are nearly \$13.5 million, or 4.92 mills per kilowatt-hour. This also equates to \$88 per tonne of materials processed (about five times greater than for conventional FGD waste disposal) or \$11 per tonne of coal burned.

This report was submitted in fulfillment of a subcontract from the Buell Emission Control Division of Envirotech Corporation under Contract No. 68-02-3119 under the sponsorship of the United States Environmental Protection Agency. This report covers the period October 2, 1979 to December 30, 1980, and work was completed January 31, 1981.

BEGIN
LAST
LINE OF
TEXT

TOP OF
SIDE AREA;
SIDE
VISION
TABLES
AND ILLUSTRATIONS

3/8"

11

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

CONTENTS

Abstract	ii
Figures	iv
Tables	vi
Abbreviations and Symbols	vii
Acknowledgment	ix
1. Introduction	1
2. Conclusions	3
3. Recommendations	5
4. Experimental Procedures	6
Objectives	6
Glass Bond Investigation	6
Pelletizing Technique Study	6
Sintering Technique Optimization	7
Study of Pellets Used as Aggregates	7
Process Flow Sheet	7
Economic Analysis	7
Experimental Approach	8
Glass Bond Investigation	8
Pelletizing Technique Study	9
Sintering Technique Optimization	10
Study of Pellets Used as Aggregates	11
Process Flow Sheet	12
Economic Analysis	14
Experimental Results	16
Glass Bond Investigation	16
Pelletizing Technique Study	27
Sintering Technique Optimization	29
Process Flow Sheet	54
Economic Analyses	64
Discussion	64
References	68

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

FIGURES

<u>Number</u>		<u>Page</u>
1	Particle size distribution of fly ash/spent nahcolite powder	19
2	Differential thermal analyses for as-received fly ash/spent sorbent mixtures	20
3	Cross section of Colorado coal fly ash particles (285X).	21
4	Cross section of lab prepared spent nahcolite particles (285X)	21
5	Batch 1 pellet microstructure (fly ash and nahcolite).	23
6	Batch 2a pellet microstructure (fly ash, nahcolite, and lime	24
7	Batch A pellet microstructures (fly ash and trona)	25
8	Thermally treated pellets containing fly ash and spent nahcolite (dried on left, fired at 1000 C on right).	30
9	Percent SO ₂ evolution from Batch 2a at various temperatures.	31
10	Effect of heating rate on SO ₂ evolution from Batch 2a.	32
11	Percent Na leached from Batch 1 after heating at various temperatures	34
12	Percent Na leached from Batch 2a after heating at various temperatures.	35
13	Percent Na leached from Batch A after heating at various temperatures	36
14	Percent Na leached from Batch C after heating at various temperatures	37
15	Percent SO ₄ leached from Batch 2a after heating at various temperatures	38

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
SIDE
EXTENSION
TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

FIGURES
(Continued)

<u>Number</u>		<u>Page</u>
16	Percent SO ₄ leached from Batch A after heating at various temperatures	39
17	Percent SO ₄ leached from Batch C after heating at various temperatures	40
18	Sulfur retention in Batch 1 after heating and leaching tests.	41
19	Sulfur retention in Batch 2a after heating and leaching tests.	42
20	Sulfur retention in Batch A after heating and leaching tests.	43
21	Sulfur retention in Batch C after heating and leaching tests.	44
22	Fractured concrete samples.	51
23	Concrete sample containing limestone aggregate.	51
24	Concrete sample containing unfired pellets.	52
25	Concrete sample containing fired pellets.	52
26	Sodium leached from concrete and asphalt samples.	55
27	Sulfates leached from concrete and asphalt samples.	56
28	Process flow diagram.	57
29	Traveling grate sintering process	59

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

TABLES

<u>Number</u>		<u>Page</u>
1	Size Distribution of Aggregate and Pellets	13
2	Experimental Mix Designs	13
3	Major Design Premises.	15
4	Dry Sorbent Chemical Composition	17
5	Sample Chemical Analyses	17
6	X-Ray Diffraction Analyses for Fly Ash/Spent Sorbent Mixtures	26
7	Batch Compositions and Pellet Strength	28
8	Leaching Test Results for Thermally Treated Pellets.	45
9	Analyses of Leachate for 100 Hour Leach Trial by Optical Emission Spectra.	46
10	Metals Analysis by Inductively Coupled Argon Plasma.	47
11	Typical Properties of Fired and Unfired Sorbent Materials (by ASTM C-127).	49
12	Comparative Strength Results for Concrete and Asphalt Test Samples After Various Curing Periods.	50
13	Sodium and Sulfate Leaching Test Results for Concrete and Asphalt Samples	53
14	Material Flows in the Process Flow Diagram	58
15	Spent Sorbent Fixation Process Equipment List, Installed Cost, and Electricity Usage.	61
16	Spent Sorbent Fixation Process (Total Capital Investment).	65
17	Spent Sorbent Fixation Process (Annual Revenue Requirements)	66

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

ASTM	-- American Society for Testing Materials
BTU	-- British thermal unit
C	-- degrees centigrade
cc	-- cubic centimeter
cm	-- centimeter
DTA	-- differential thermal analysis
EPA	-- United States Environmental Protection Agency
FGD	-- flue gas desulfurization
ft ³	-- cubic feet
g	-- gallons
hr	-- hour
IRI	-- Industrial Resources Inc.
k\$	-- thousands of dollars
k ft ³	-- thousands of cubic feet
kg	-- kilograms
gal	-- thousands of gallons
kℓ	-- thousands of liters
kWh	-- kilowatt-hours
ℓ	-- liters
lb	-- pound
M\$	-- millions of dollars
m ²	-- square meters
m ³	-- cubic meters
mills	-- \$0.001 (one-tenth of one cent)
Mg	-- megagrams
MW	-- megawatts
μg	-- micrograms
μm	-- micrometers
ppb	-- parts per billion
ppm	-- parts per million
psi	-- pounds per square inch
TVA	-- Tennessee Valley Authority
yr	-- year

SYMBOLS

\$	-- dollars
%	-- percent
>	-- greater than
<	-- less than

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

CONVERSION FACTORS

English Units

BTU
gallon
ft³
lb
ton

SI Units

1.055 x 10³ joules
3.785 liters
2.830 x 10⁻² cubic meters
4.536 x 10⁻¹ kilograms
9.070 x 10⁻¹ tonne

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

3/8"

viii

PAGE NUMBER

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

ACKNOWLEDGMENTS

The laboratory assistance of Mr. James Turner, Mr. Tom Rackner, Mr. Jim Telljohann, and Ms. Jill Jonkouski is gratefully acknowledged.

The U. S. Bureau of Mines supplied the nahcolite for the pilot plant experiments from their research tract near Grand Junction, Colorado.

The City of Colorado Springs, Colorado through Mr. Ron Ostop in the Department of Public Utilities was most helpful in providing the power plant facilities required to conduct the pilot plant dry injection experiments.

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

3/8"

ix

PAGE NUMBER

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

SECTION 1

INTRODUCTION

Recent trends in sulfur dioxide emission controls have included the use of fabric filters or electrostatic precipitators for particulate control, and wet lime or limestone scrubbing for control of sulfur dioxide from the boiler flue gas (1). Alternative flue gas desulfurization (FGD) processes in various stages of research currently include spray drying and dry injection of sorbents into the boiler flue gas stream. Dry injection of sorbents is desirable in arid regions of the country where water is scarce and western coals with lower sulfur contents than eastern coals are available.

The Buell Emission Control Division of Envirotech Corporation has tested a dry FGD process at the Martin Drake Power Plant in Colorado Springs, Colorado which involved the injection of nahcolite (NaHCO_3) or trona ($\text{NaHCO}_3 \cdot \text{Na}_2\text{CO}_3$) into a flue gas stream from one of the boilers in the plant. The resulting fly ash/spent sorbent mixtures were collected in a pilot baghouse or the baghouse at the facility.

The primary problem associated with the dry injection FGD process using sodium compounds is disposal of the spent sorbent, which is highly water soluble, forming sodium sulfate and sodium sulfite when reacted with the SO_2 in the flue gases.

In a previous study at Battelle sponsored by Industrial Resources Incorporated (IRI), the problem of disposal of spent nahcolite from dry FGD processes was addressed (2). The laboratory program included glass melting studies and sintering experiments, which eventually led to development of the patented Sinterna process for consolidation and sintering of material by-products containing spent nahcolite sorbent. In the glass melting studies, significant phase separation occurred in most of the melted glasses containing the fly ash/spent sorbent mixtures as a soda ash replacement (in addition to other components). The most promising results were obtained during sintering experiments which indicated partial stabilization of the sulfate-containing fly ash/spent mixtures through agglomeration and sintering at temperatures up to 950 C. These tests were conducted on simulated fly ash/spent sorbent mixtures in various ratios.

An objective of the present study was to obtain real spent nahcolite and spent trona by-products mixed with fly ash which would be truly representative of real conditions in a dry FGD system. These materials were obtained from Envirotech's pilot facility at Colorado Springs and were tested in Battelle's laboratory to determine the optimum conditions for agglomeration and sintering

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

1

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

which would stabilize the fly ash/spent sorbent mixtures for possible disposal in a simple landfill. The economics of this process for a typical 500 MW power plant in the Great Plains-Rocky Mountains area burning low sulfur western coal were also to be determined.

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

6-1/2"

9-1/8"

BEGIN
LAST LINE
OF TEXT

3/8"

2

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD.
BEGIN
SECTIONS
HERE

SECTION 2

CONCLUSIONS

A conceptual process flow diagram and equipment description have been prepared for a facility which would process and somewhat stabilize alkaline fly ash/spent sorbent mixtures from a dry flue gas desulfurization (FGD) system for a 500 MW power plant burning low sulfur western coal. The process includes dual disc pelletizing circuits and a traveling grate furnace with an output of nearly 590 tonnes per day of pellets sintered to a temperature between 950 C and 1000 C.

In laboratory tests, pellets containing fly ash and either spent nahcolite or spent trona (both reacted with SO_2), when thermally treated at 1000 C and mildly stirred in water for 100 hours, lost from 30 percent to 60 percent of the total sulfur in the pellets as SO_2 evolved or SO_4 leached. The amount of sodium leached under similar conditions ranged from 3 to 15 percent of the amount available.

Some stabilization of the soluble alkaline sulfates occurs during thermal treatment through sintering mechanisms and formation of new compounds, such as $\text{Na}_6\text{Ca}_2\text{Al}_6\text{Si}_6\text{O}_{24}(\text{SO}_4)_2$ which was identified by X-ray diffraction in pellets fired at 1000 C.

The encapsulation of dried pellets or pellets fired at 925 C in concrete or asphalt mixes did not significantly inhibit the leaching in water of the soluble alkaline sulfates from the pellets. In compressive strength tests, cured concrete samples and asphalt samples containing pellets on a 20-percent-by-volume substitution for limestone aggregate exhibited losses in strength of 50 percent and 75 percent, respectively. These strength losses were attributed to the high porosity of the pellets, requiring higher water to cement ratios in the concrete mixes and higher pitch contents in the asphalt mixes.

Although these preliminary laboratory technical results are not particularly encouraging, this sintering process for the stabilization of by-products from a dry FGD system can be more thoroughly evaluated only by pilot-scale testing. Pilot plant trials would also aid in more detailed engineering design and costing of a full-scale facility.

The cost estimates for a dry FGD by-product stabilization facility for a 500 MW power plant are nearly \$20 million in total capital required, or \$40.55 per kilowatt. The levelized annual revenue requirements are nearly \$13.5 million, or 4.92 mills per kilowatt-hour. This also equates to \$88 per tonne of FGD waste processed (about 5 times that for conventional FGD waste disposal), or \$11 per tonne of coal burned.

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
LAST LINE
OF TEXT

These costs may be prohibitive towards further consideration of this type of process for the stabilization of dry FGD by-products. However, increasing the utilization of the facility by processing additional material, or improved engineering design and pilot-scale testing of the facilities, should result in more favorable processing economics.

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

These costs may be prohibitive towards further consideration of this type of process for the stabilization of dry FGD by-products. However, increasing the utilization of the facility by processing additional material, or improved engineering design and pilot-scale testing of the facilities, should result in more favorable processing economics.

6-1/2"

8-1/8"

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

4

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

SECTION 3

RECOMMENDATIONS

More detailed engineering design and pilot-scale testing of the sintering process for stabilization of dry FGD by-products is needed to provide input for more accurate cost estimates for the process. Also, testing of pellets under more realistic processing conditions would help to determine absolutely whether the balance of sulfate evolution during thermal processing and leachability of soluble compounds in water would be acceptable in engineering terms and according to regulatory guidelines.

Since the preliminary technical and economic results generated during this project are not entirely in favor of a sintering process for dry FGD by-products from a 500 MW power plant, alternative methods of disposal should still be considered. The economics and technical considerations of disposal in clay-lined cells or regeneration with other compounds to stabilize the soluble compounds should still be considered, as well as other alternatives which might be identified.

BEGIN
LAST LINE
OF TEXT

3/8"

5

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTION'S
HERE

SECTION 4

EXPERIMENTAL PROCEDURES

OBJECTIVES

Glass Bond Investigation

In order to optimize the stabilization of the sorbent/fly ash mixtures, an understanding of the influence of thermal processing on the development of a glassy bonding phase in the agglomerates was desired. The influence of the glassy phase and other microstructural elements of the agglomerates on strength and chemical durability was to be determined through various analytical techniques. These techniques included compositional analysis, microstructural analysis by light microscopy and scanning electron microscopy, and structural analysis by X-ray diffraction techniques.

The effect of small amounts of additives, such as binders used for agglomeration, on the stability of the thermally processed agglomerates was also to be determined. All of the results from the glass bond investigation were to be compared to results obtained from other laboratory investigations involving the sintering and leaching of the agglomerates.

Pelletizing Technique Study

The agglomeration technique chosen for the spent sorbent/fly ash stabilization process was disc pelletizing, due to its widespread use for agglomerating similar materials on a large volume basis. Pellets are formed in a disc pelletizer by continuous rolling and compaction of the feed material into spheres of a desired size distribution, usually by spraying water onto the material to initiate the agglomeration of the particles in the feed material. The feed material often requires an additional binder as a pelletizing aid to enhance pellet green strength for handling purposes. The main objectives of the pelletizing technique study were to determine the pelletizer operating parameters required to produce pellets from the spent sorbent/fly ash mixtures in a satisfactory size range and with sufficient handling strength, and to determine the pelletizing moisture and binder requirements for the feed material. Binders to be considered initially included sodium silicate, bentonite, lignosulfonate, burned lime, and hydrated lime.

The results of the pelletizing technique study were tied in with the glass bond investigation and sintering technique optimization, since the pellets were required to maintain sufficient handling strength during thermal

BEGIN
LAST
LINE OF
TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3 7/8"

6

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

processing. It was known from previous work in glassy materials that the bonds contributing to green strength of the pellets weaken considerably with increasing temperatures.

Sintering Technique Optimization

During this part of the laboratory program, it was desired to determine the optimum time and processing temperatures for thermally treating the green pellets in order to maximize sulfur retention based on SO₂ evolution and sulfate leaching tests. Individual pellets of the various compositions made during the pelletizing studies were to be subjected to a controlled heating cycle, during which the amount of SO₂ evolved was to be measured. These pellets were then to be leached for various times up to 1000 hours in distilled water under moderate stirring.

Based on the results from the pelletizing and sintering studies, a commercially available sintering furnace was to be chosen as suitable for the stabilization process, and which would be used for costing purposes in the process economic analysis.

Study of Pellets Used as Aggregates

In order to study various disposal or recycling alternatives for the spent sorbent/fly ash pellets, it was necessary to determine the effect of partial substitution of these pellets for other aggregates in portland cement concrete and asphalt mixtures. The objectives were to determine material properties, such as pozzolonic activity, specific gravity, and absorption, and then evaluate strength and sodium and sulfate leachability from the concrete and asphalt mixtures.

Process Flow Sheet

A process flow sheet was needed as a basis for the economic analyses of the stabilization process and for basic design considerations of an actual plant operation. The objectives were to obtain a list of materials and equipment requirements, equipment costs and operating costs, and a materials balance for a typical operation.

Economic Analysis

The ultimate objectives of the process economic analysis were to determine the capital cost of the facilities in dollars per kilowatt of generation capacity and the estimated annual operating costs in mills per kilowatt-hour. These were to be based on the information obtained in developing the process flow sheet and the basic economic analysis assumptions made in a previous EPA report (1).

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

EXPERIMENTAL APPROACH

Glass Bond Investigation

DROPPED
HEAD
BEGIN
SECTIONS
HERE

In a previous study for Industrial Resources, Inc. (IRI) (2), it was recognized that the development of a glassy bonding phase during thermal treatment of the agglomerated fly ash/spent sorbent mixtures would influence the solubility of the leachable components in the material. However, it was also recognized that raising the temperature for thermal processing increased the probability of evolving SO_2 from the material in the furnace. This study was thus concerned with stabilizing the leachable constituents of the mixtures through thermal processing while minimizing the SO_2 evolution in the process.

Similar problems of minimizing leaching of sulfate compounds from ceramic products such as tiles and bricks have been studied extensively. Brownell (3,4,5) conducted studies on efflorescence of soluble compounds (or scum) for clay products by introducing soluble salts into clay bodies, firing them at various temperatures up to 1100 C, and then determine the amount of soluble sulfate remaining after firing. He also determined a preferential order of sulfate compound formation in clay bodies containing (in order) K_2O , Na_2O , BaO , CaO , MgO , and FeO according to heats of reaction and analytical considerations. Since the clay body compositions were somewhat similar to the compositions of the fly ash/spent sorbent mixtures to be studied during the present program, it was felt that similar results would be obtained and that various additives to the mixtures might help to stabilize the processed materials.

Another approach to studying the stabilization of the thermally processed materials was to assume that some reactions of the sulfates with the fly ash during thermal processing would either result in absorption of some of the SO_2 by the glassy phase or the formation of complex aluminosilicate sulfate compounds, as determined in previous studies (3,6). In order to investigate the ceramic processing approaches for these materials, it was first necessary to characterize the starting materials.

Several studies have been completed on the characterization of fly ashes from coal burning power plants (7,8). A TVA report (9) states that fly ash is comprised primarily of the oxides of silicon, aluminum, calcium, iron, and other minor elements. Petrographic analyses indicate that fly ashes are generally 50 to 90 percent glass by weight, with the remaining material being primarily quartz, mullite, hematite, magnetite, and carbon. The glassy phase contains a considerable amount of material known as cenospheres, which are rounded particles containing nitrogen and carbon dioxide, comprise 5 to 20 percent by volume of the total fly ash, and range from 20 μm to 200 μm in diameter.

Some of the fly ash/spent sorbent mixtures received from Envirotech were analyzed for physical properties, such as surface area and particle size distributions in Battelle's powder characterization laboratory. Particle size distribution was determined by sedimentation methods, and the surface area was determined in a Micrometric Model 2205 surface area analyzer. Chemical analyses were performed in Battelle's analytical chemistry laboratory according to standard techniques.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

3/8"

8

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

Samples of pressed pellets were obtained from the previous IRI study (2) and corresponded to the nominal fly-ash-to-spent-sorbent weight ratio of 75/25. Some of the as-pressed samples and samples which had been fired up to 1100 C were cut and polished. The microstructures of these pellets were observed and characterized under reflected light microscopy and by ion microprobe analysis. Powders used and pellet samples made during the current program were also mounted and polished and characterized by reflected light microscopy and by a scanning electron microscope (SEM) with energy dispersive X-ray analysis capabilities.

Several samples of dried and fired pellets made during the program were analyzed for crystalline content in a Norelco diffractometer, using Cu K α radiation. These results were combined with microstructural analyses conducted by optical microscopy to study the change in crystalline content and compound formation in the pellets during thermal processing.

Pelletizing Technique Study

Due to the very fine particle size distribution, fly ash disposal presents difficult handling problems as well as potential for airborne particulate pollution. In order to handle a relatively large tonnage (>20 tons per hour for a 500 MW facility) of fly ash/spent sorbent mixtures in the waste stabilization process, disc pelletizing was chosen as the preferred powder agglomeration method. Disc pelletizing and sintering of fly ash has been used for many years for lightweight aggregate production (7,10) and is mentioned in two recent patents as the preferred agglomeration method for fly ash waste disposal (11,12).

Disc, or pan, pelletizing involves feeding a powdered material onto a rotating disc and spraying water or another liquid onto the powder to initiate agglomeration of the individual powder particles (13). The liquid acts as a binder while the powder is rolling and tumbling in the pelletizing into spheres of a narrow size distribution determined by the operating parameters and raw material variables. The operating variables include pan angle and depth, rotational speed, water spray and feed material rates and location, and scraper location. Raw material variables include particle shape and size distribution, compositional variability, and binder type and amount.

The initial pelletizing experiments were conducted using small batches (~2 kg) of the fly ash/spent sorbent mixtures with and without additional binders added for green strength. These batches were pelletized in a small pelletizer with a diameter of 36 cm and a depth of 16 cm. Pellets were made ranging from 5 mm to 15 mm in diameter and were tested for strength using a hand-held spring compression device. The force required to break the dried or fired pellets was measured and recorded. The binders selected for comparison of their green strength contribution included calcium lignosulfonate, bentonite, hydrated lime, and limestone and were added in amounts from 2 to 5 percent of the original batch weight.

BEGIN
LAST LINE
OF TEXT

Pilot-scale production of several hundred pounds of pellets were conducted using two larger pelletizing units with different rim-height-to-diameter ratios. A deep drum pelletizer (Mars Mineral Corporation Series 20)

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

with a rear feed screw, a diameter of 61 cm, and rim depth of 45 cm was used initially in attempts to pelletize the fly ash/trona sorbent powder received from Envirotech from a pilot test run at the Martin Drake Power Plant in Colorado Springs. More of the trona-containing mixtures and the fly ash/nahcolite mixtures were later pelletized in a shallow disc pelletizer which had a diameter of 106 cm and depth of 22 cm. The pellets from the later trials were dried at 150 C, fired at 925 C, and used as aggregate in the concrete and asphalt mixture testing.

Sintering Technique Optimization

Sintering of pellets containing fly ash and simulated spent nahcolite sorbent was studied in the previous IRI program (2). SO₂ evolution during firing and sulfates leached from fired pellets were measured during that program which indicated that the pellets could be stabilized with up to 75 percent total sulfur retained after thermal processing up to 1100 C and leaching for 100 hours. Since these experiments were conducted on laboratory-prepared fly ash/spent nahcolite mixtures, similar tests on mixtures of fly ash and spent sorbent obtained from the Envirotech pilot plant were to be conducted during the present program.

Previous studies of the thermal behavior of sulfates in ceramic materials, such as the Differential Thermal Analysis (DTA) results reported by Gruver (14), show that alkali metal sulfates in general are volatile without decomposing at high temperatures (>1100 C) and melt at lower temperatures. Sodium sulfate, which is a primary reaction product of the sodium-containing sorbents with flue gas, has been shown to melt at 880 C, although its volatility can be influenced by the atmosphere and the presence of carbon. Calcium sulfate dissociates at 900 C, while barium sulfate melts at 1580 C. Calcium sulfate and barium sulfate are considerably more water insoluble than sodium sulfate, and the possibility of stabilizing the spent sorbent by forming these compounds using various additives and processes was investigated early in the program.

The apparatus for measuring SO₂ evolution consisted of a fused silica tube inside a tube furnace, in which the individual pellets were heated to the desired temperature. Compressed dry air was passed through the tube over the samples during heating, allowing the air to pick up the SO₂ evolved. These gases were passed through a 3 percent hydrogen peroxide solution, where the pH was monitored continuously and recorded along with the temperature inside the furnace to show SO₂ evolution versus temperature. The total amount of SO₂ evolved was determined after each experiment by titration of the SO₂-containing hydrogen peroxide solution with a standardized sodium hydroxide solution.

Dried and fired pellets were leached in 100 ml of deionized water at room temperature with mild stirring in covered Pyrex beakers. Ten milliliter samples of the liquid were drawn after 1, 10, and 100 hours for chemical analyses of the sodium and/or SO₂ concentrations to determine the leaching rate of these ions from the samples. Heavy metal content was analyzed in one sample by optical emission spectroscopy (OES). A proposed ASTM standard procedure described by Webster (15) for extraction of leachate from waste materials was reviewed and considered for these tests but was not suitable for

potentially friable agglomerates, such as those made in the Sinterna process (agglomeration and sintering process patented by IRI), since it involved a shaking procedure in the method. Cation solubilities of lignite fly ashes reported in the literature (16) indicate high solubilities of sodium and calcium sulfates at various water-to-fly-ash ratios. The solubility of these compounds was shown to vary considerably, depending on the source of the ash and whether the samples were taken from an electrostatic precipitator or a baghouse. The Sinterna process has been proposed as a means of "stabilizing" the cations and sulfates in the discarded fly ash/spent sorbent mixtures from the dry injection process for SO₂ control from coal-burning power plants. Otherwise, runoff and leaching water salt contents from landfilled material could probably exceed allowable limits.

Although the pellet heating experiments were conducted in electric furnaces during the program, actual industrial practice for sintering the fly ash pellets generally involves a gas- or oil-fired furnace. There is considerable practical experience in producing lightweight aggregate from fly ash in traveling grate furnaces (7,10,17), and discussions with designers of this type of equipment indicated that the previous experience is not entirely applicable to the present problem of sintering fly ash/spent sorbent mixtures containing greater than 3 percent sulfates and/or sulfites. However, it was decided that the basic traveling grate design, although most suitable for the process, would require more elaborate process controls and equipment. The production capacities for typical traveling grate or circular grate furnaces for iron ore processing range from 1 to 12 Mg per day. The nominal output from the proposed 500 MW power plant would be nearly 0.5 Mg per day, which is small in comparison with the iron ore facilities.

Study of Pellets Used as Aggregates

Numerous studies have been reported on the use of fly ash for different applications, including structural fill (7,10), lightweight aggregates (7,10,17), cement and concrete fill (7,10,12,17,18), asphalt fill (7,10,15,19), land reclamation (7), bricks (7,10), mineral recovery (7,10), and numerous other uses (2,7,10,15,19). Although it has been estimated that nearly 91 million tonnes per year of coal ash (70 percent of which is fly ash) will need to be disposed of by 1985 (20), less than 20 percent will be recycled and the remainder will need to be landfilled.

Since the output of the Sinterna process consists of fly ash/spent sorbent-containing pellets ranging from roughly 5 mm to 15 mm in diameter, this material is potentially useful as an aggregate in portland cement concrete and bituminous mixes. An objective of the present program was to determine whether the cement or asphalt binding phase of the mixtures would serve to further stabilize the pellets by preventing leaching of the alkalis and sulfates from the pellets. Another interest was the influence of the pelletized material on the physical properties of the concrete and asphalt specimens, most specifically in the compressive strength development with

aging. The tests conducted during this part of the program were intended as screening evaluations for comparison of concrete and asphalt mix properties with and without the fly ash/spent sorbent-containing pellets.

Bulk specific gravity, apparent specific gravity, and percent water absorption were determined for the unfired and fired pellets according to ASTM Standard Test Method C127. These results indicated the degree of densification of the pellets during firing, which would affect the water and pitch requirements in the concrete tests and asphalt tests, respectively. The pozzolanic activity index of the powder used to make the pellets was 89 percent according to ASTM C311. This gives some indication of the highly cementitious nature of the untreated fly ash/spent nahcolite mixtures.

Both the portland cement concrete and asphalt test specimens were made utilizing crushed limestone and fly ash/spent nahcolite-containing pellets. The size distribution of the limestone and the pellets used is shown in Table 1. The mix designs for the test samples are shown in Table 2.

The concrete mix was cast into cylinders 7.6 cm in diameter by 15.2 cm long from mixes made with 12.7 cm slump. Some of the samples were cured at 21 C and 100 percent relative humidity prior to compressive strength testing according to ASTM C29. Some samples were cured for 14 days prior to being used for the leaching tests.

The asphalt samples were prepared by the Marshall Test Method (ASTM D1559) and cast into cylinders 10.2 cm in diameter by 6.4 cm long. The samples were strength tested in radial compression according to the test procedures.

For the leaching tests, samples were placed in sealable plastic containers in distilled water. The ratio of water to specimen volume was 1.6 and specimens were surrounded on the top and sides by at least 2.5 cm of water. The sample containers were agitated daily. Samples of 100 cc of water were withdrawn from the containers at prescribed intervals and were analyzed for sodium and sulfur by atomic absorption analysis. The water taken for the analyses was replaced by 100 cc of fresh distilled water.

Process Flow Sheet

Developing a process flow sheet for the Sinterna process was rather straightforward once the method of agglomeration and type of sintering furnace were selected. Disc pelletizing and sintering have been used to prepare iron ores in direct reduction processes for several decades. The direct experience gained from these processes is applicable to the agglomeration and sintering of many other materials, including fly ash. Also, lightweight aggregate has been made for many years in Great Britain based on this same process.

Czako et al. (22) have discussed the importance of laboratory testing of materials as the basis for design and engineering of pelletizing and sintering plants. Laboratory tests have indicated the optimum time and temperature ranges of thermal processing for maximum sulfur retention in the fly ash/spent sorbent pellets, but these tests need to be supplemented by more

DROPPED
HEAD
OPTION

TABLE 1. SIZE DISTRIBUTION OF AGGREGATE AND PELLETS

Sieve Size	#8 Limestone	Percent Passing	
		Unfired Pellets	Fired Pellets
1/2 in.	100	100	100
3/8 in.	89.15	93.20	87.50
4 mesh	17.70	18.20	33.90
8 mesh	5.40	3.80	4.80
16 mesh	3.30	0.20	0.20

TABLE 2. EXPERIMENTAL MIX DESIGNS

Concrete Samples			
Material	Mix #1 Mass (kg)	Mix #2 Mass (kg)	Mix #3 Mass (kg)
Cement	13.6	13.6	13.6
Sand	27.3	27.3	27.3
#8 Limestone	27.3	21.8	21.8
Fired Pellets	-	4.3	-
Unfired Pellets	-	-	4.4

Asphalt Samples			
Material	Mix #1 Mass (grams)	Mix #2 Mass (grams)	Mix #3 Mass (grams)
Pitch	150	560 ^(a)	560 ^(a)
Limestone Dust	90	90	90
#8 Limestone	2760	2208	2208
Fired Pellets	-	432	-
Unfired Pellets	-	-	441

(a) Pitch content was varied to coat aggregate and provide workability.

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

extensive testing so that a plant design based on more accurate material balances can be proposed. However, the rough initial plant design, material balances, and process economics were determined after discussions with representatives of the Davy McKee Corporation, who were most cooperative in their discussions, but understandingly cautious in attempting to provide specific operating parameters and equipment designs for material which had not been tested in their laboratories.

Preliminary discussions with Davy McKee representatives have also indicated that traditional sintering grate operation may not apply to the processing of the fly ash/spent sorbent containing pellets, due to the temperature restrictions and degree of control required. The sintering grate design selected was based on best estimates, while being quite conservative by allowing a lower load estimate and higher grate factor.

Material balances and utility requirements were based on best estimates drawn from previous experience with similar processes.

Economic Analysis

In order to provide cost information from the economic analysis which could be compared to that already generated for other FGD processes, all of the basic premises used for the analysis are similar to those contained in recent reports by the TVA for the EPA (1,23). The desired output from the economic analyses included total capital investment, total capital per kW of generation capacity, and annual revenue requirements based on operating and maintenance costs.

The major plant design premises are shown in Table 3. The base-case power plant is a new, 500 MW coal-fired unit in the Great Plains-Rocky Mountain region. The fuel is a subbituminous coal containing 0.7 percent sulfur and 9.7 percent ash. For the economic analyses, the basis for the capital investment costs is mid-1982, while the revenue requirements are based on 1984 costs. For complete details of the methods used to calculate the various factored capital costs and annual operating and maintenance costs, the reader is referred to the previously mentioned EPA reports (1,23).

The capital investment estimates include direct investment in installed equipment, indirect investment in related expenses, and other costs such as allowance for startup and modification which are factored from the direct and indirect investment costs. All of the estimates are based on a process description, flowsheet, material balances, and equipment list. Equipment costs were obtained from vendor estimates, catalogs, and various cost estimating guides used in the chemical engineering and mining engineering fields (24,25,26,27,28). Weaver (25) in the Chemical Engineer's Handbook also offers guidelines on labor costs for installation of equipment. Most references indicate that capital investment estimates such as these have a -20 percent to +40 percent range of accuracy.

BEGIN
LAST LINE
OF TEXT

The factored capital charges were based on guidelines established in the previous EPA reports and in various publications on capital cost estimating (25,27). In the direct investment category, building and site development was

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 3. MAJOR DESIGN PREMISES

Item	Premise
Power Plant	New, Great Plains - Rocky Mountain region, 500-MW coal-fired boiler, 9,500 Btu/kWh heat rate
Operating Schedule	165,000 hr; 30-yr life, 5,500-hr first-year operation
Fuel	Subbituminous coal; 9,700 Btu/lb, 0.7% sulfur, 9.7% ash, 16% moisture
Base Year	Capital investment: mid-1982 Revenue requirements: 1984
FGD Waste Disposal	Pelletizing and sintering to stabilize for landfill
SO ₂ Removal Efficiency	70%

BEGIN
LAST LINE
OF TEXT

3/8"

15

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

factored at 60 percent of the fixed capital charges, while services, utilities, and miscellaneous expenses were costed at 6 percent of the fixed investment.

DROPPED
HEAD
BEGIN
SECTIONS
HERE

In the indirect investment category, engineering design and supervision had a 7 percent factor, architect and engineering contractor expenses were 2 percent, construction expense was 16 percent, and contractor fees were 5 percent, all based on total direct investment. Contingency funds were allocated at 10 percent of the total of the direct and other indirect investment costs.

Other capital charges included allowances for startup and modification at 10 percent of direct investment, interest during construction based on 15.6 percent of the fixed costs, and working capital costs based on 3.4 percent of direct costs.

Annual revenue requirements are based on 5,500 hours of operation per year at full load and consist of direct and indirect costs. First year and levelized annual revenue requirements are determined, with the levelized annual revenue requirements being based on a 10 percent discount factor and a 6 percent inflation rate over the 30-year life of the facilities. The only factored direct costs are maintenance charges, which are based on 7 percent of the total fixed capital investment costs.

EXPERIMENTAL RESULTS

Glass Bond Investigation

The concept of using an additive such as barium carbonate in an attempt to stabilize the sulfate in the fly ash/spent sorbent mixtures was dropped from consideration early in the program when calculations showed that barium carbonate in amounts up to 26 percent by weight of the mixture would be required to fully react with the sulfates. Since barium carbonate costs over \$400 per ton, this would not be an economical processing alternative, as even a 5 percent addition of barium carbonate would add a cost of \$20 per ton of finished product.

Chemical analyses provided by Envirotech of the nahcolite, trona, and refined trona used as sorbents in their dry injection tests are shown in Table 4. The nahcolite was obtained from the U. S. Bureau of Mines from a deposit in Rio Blanco County, Colorado, while the trona was taken from Owens Lake in California. Table 5 contains analyses of pure fly ash (average of several samples), the fly ash/spent nahcolite from Envirotech tests 12R1, and the fly ash/spent trona from Envirotech test 22R1 at its pilot facility at the Martin Drake power plant in Colorado Springs. Several hundred pounds of the materials were used in laboratory tests at Battelle. The Battelle analyses at the bottom of Table 5 were used as the basis for calculations in the sulfate evolution and leaching tests, since there was a discrepancy between the Battelle and Envirotech analyses. Cross checks of test results later in the program indicated that the Battelle results were more representative of the actual compositions. One interesting point in the analyses is the ratio of

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 4. DRY SORBENT CHEMICAL COMPOSITION

Dry Sorbent	Envirotech Number	Chemical Analysis, Weight Percent						
		NaHCO_3	Na_2CO_3	NaCl	Na_2SO_4	Na_2SO_3	NaNO_3	Water
Nahcolite	N-5A	52.76	3.64	0.49	0.40	0.001	0.02	1.83
Nahcolite	N-5B	54.01	3.13	0.46	0.32	0.002	0.03	2.04
Refined Trona	B-1	59.32	14.22	1.27	1.19	<0.001	<0.01	8.7
Trona	T-1	26.43	41.39	4.14	5.19	<0.001	<0.01	13.2

NOTE: Chemical Analyses provided by Buell Emission Control Division, Envirotech Corporation.

TABLE 5. SAMPLE CHEMICAL ANALYSES

Description	Weight Percent											Total
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_5	TiO_2	Li_2O	
Fly ash from Colorado Springs Plant - Averages	66.80	4.00	17.50	4.40	1.50	0.26	1.07	1.50	0.80	0.80	0.02	98.65
Fly ash/ spent nahcolite - Test 12R1	51.22	3.23	22.83	3.60	1.49	2.90(a)	1.21	3.42(a)	1.31	0.78	0.02	99.56
Fly ash/ spent trona - Test 22R1	52.14	5.23	21.08	3.63	1.21	2.78(b)	1.08	4.93(b)	1.26	0.86	0.02	99.55

NOTE: Chemical Analyses provided by Buell Emission Control Division, Envirotech Corporation.

(a) BCL Analyses: $\text{SO}_4^{2-} = 3.59$, $\text{SO}_3 = 0.16$, $\text{Na}_2\text{O} = 3.05$.

(b) BCL Analyses: $\text{SO}_4^{2-} = 7.06$, $\text{SO}_3 = <0.2$, $\text{Na}_2\text{O} = 8.64$.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

sulfate to sulfite sulfur content. The high sulfate to sulfite ratio, as analyzed in these samples, is more desirable for the Sinterna waste stabilization process since sulfates are more stable at higher processing temperatures. It should be noted, however, that previous tests at Battelle for IRI showed that this ratio could be just the opposite under some FGD dry injection conditions using sodium compounds and that exposure to oxygen in a higher temperature range would be required to convert the sulfites to sulfate compounds.

The fly ash/spent nahcolite powder received from Envirotech is dark grey in color, and its particle size distribution ranges from 1 to 60 μm in diameter, with a median particle diameter of 15 μm (see Figure 1). The surface area as measured on a Micrometrics model 2205 analyzer is 4.5 m^2/g , which is somewhat higher than that predicted from the particle size distribution, but may be due to internal porosity in the nahcolite particles which increases effective surface area.

The fly ash/spent trona received from Envirotech is a much lighter grey color than the nahcolite-containing powder, which may indicate just from appearance that this material has a higher spent-sorbent-to-fly-ash ratio. This would further verify the results of the BCL chemical analyses of the powders which indicated that the trona-containing mixtures had higher soda and sulfate contents than the nahcolite-containing mixtures.

Differential Thermal Analyses (DTA) of the powders as received are shown in Figure 2. The only significant result of these tests indicates that some exothermic reactions occur over a temperature range from 400 C to 650 C in the fly ash and fly ash/spent nahcolite samples, which is not as pronounced in the fly ash/spent trona sample. These reactions are attributed to burning of the residual carbon from unburned coal in the samples.

Samples of the fly ash/spent nahcolite powder were placed on a hot stage and observed for visible reactions under a microscope for temperatures up to 935 C. Over a range from 180 C to 260 C, some particles moved slightly due to loss of absorbed moisture. At 600 C the sulfate reaction layer on the nahcolite particles changed from red to yellow, while at 770 C the nahcolite particles appeared to melt. From 800 C to 820 C, a liquid coating appeared over most of the fly ash particles, and by 880 C there was some sintering together of the fly ash particles. These observations were used for guidelines for thermal treatment of pellets and verification of the microstructural analyses.

A sample of the fly ash from the Colorado Springs plant was dispersed in epoxy and polished to provide a cross section of the fly ash particles for microscopic observation, as shown in Figure 3. The rounded glass cenospheres are most prominent in the micrograph, while the irregular-shaped particles are primarily quartz. One important observation to note is the occurrence of crystalline matter in the center of many of the rounded fly ash particles. This material is probably high in alumina content (mullite) and is refractory enough to remain essentially unchanged through further thermal treatment, as will be discussed later in this section of the report.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

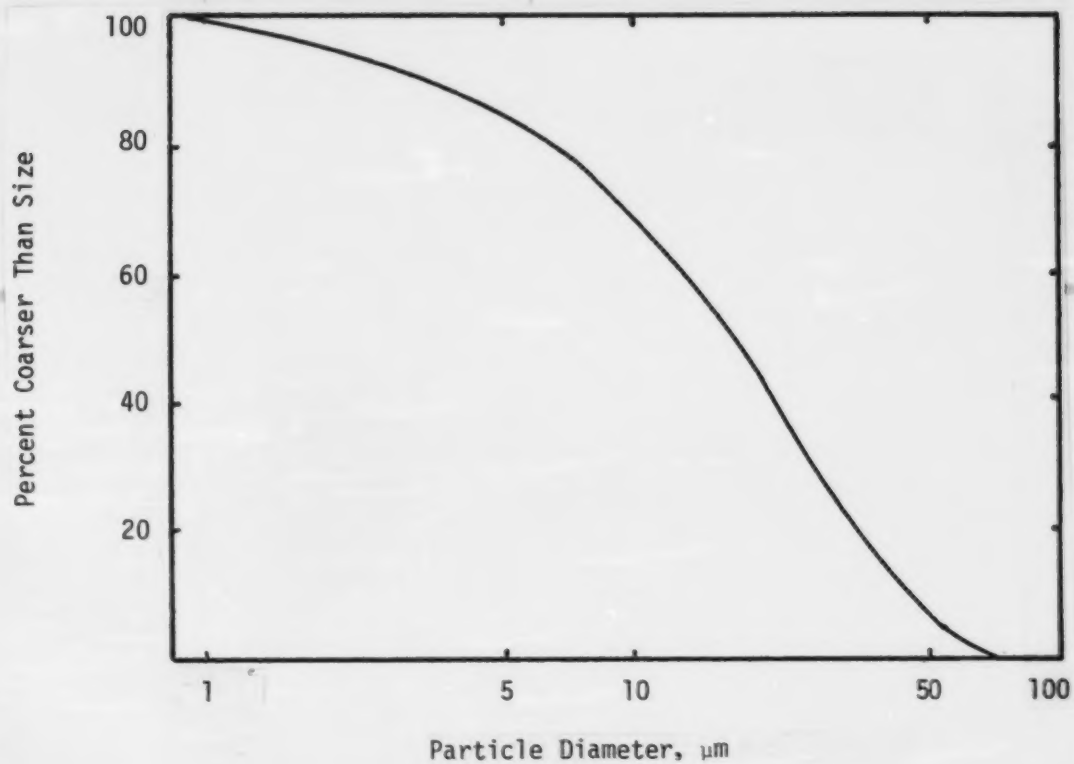
BEGIN
FIRST
LINE OF
TEXT
HEREDROPPED
HEAD
BEGIN
SECTIONS
HERE

Figure 1. Particle size distribution of fly ash/spent nahcolite powder.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

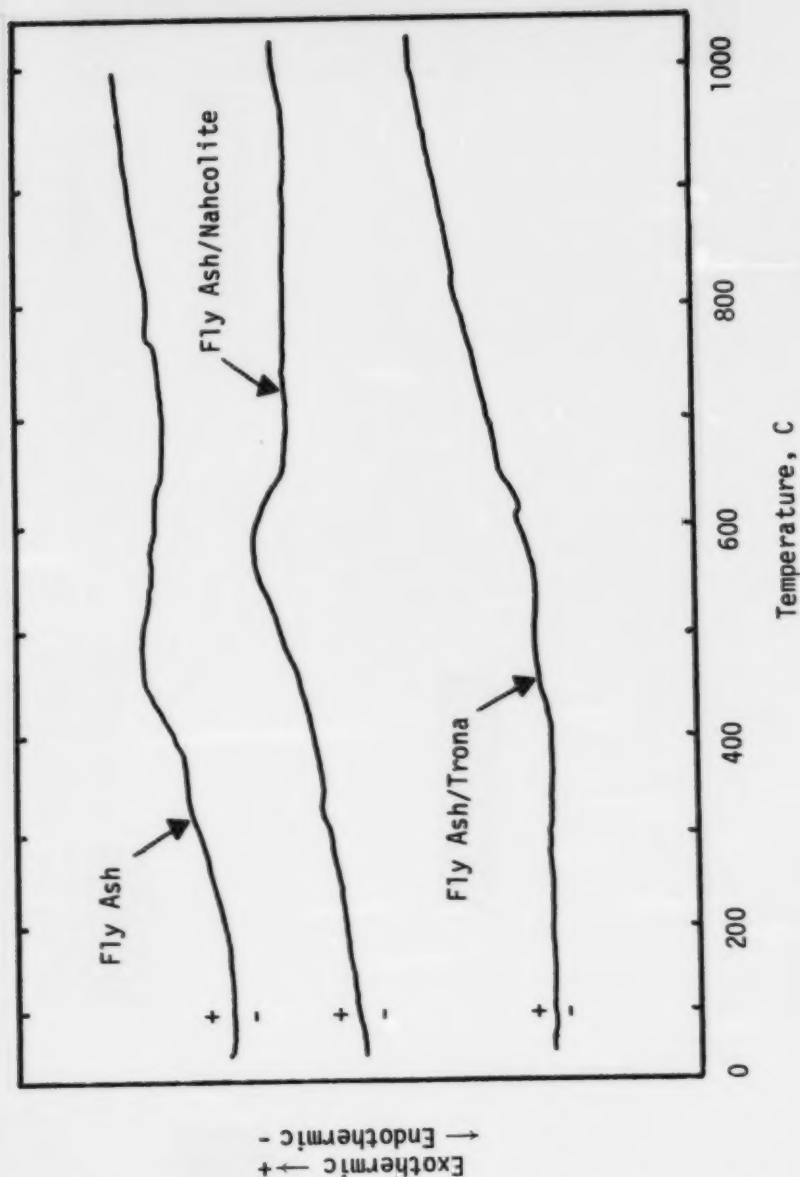


Figure 2. Differential thermal analyses for as-received fly ash/spent sorbent mixtures.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

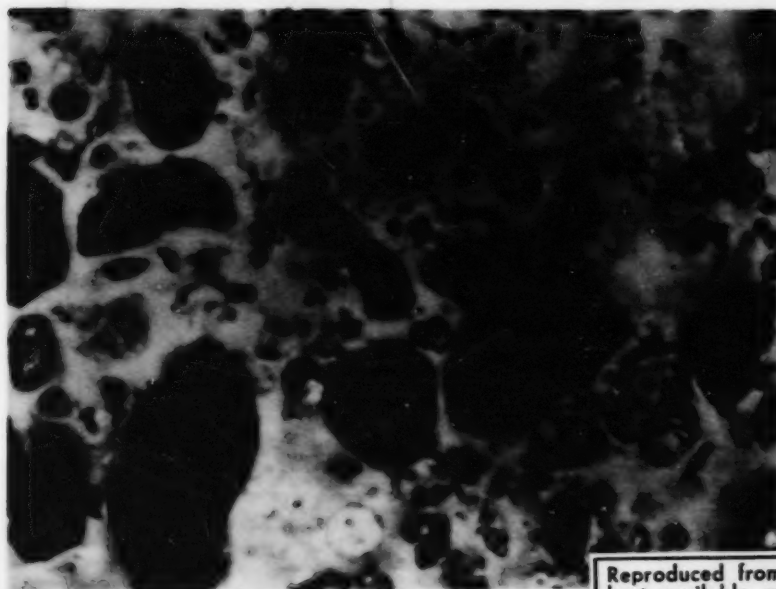
CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD:
BEGIN
SECTIONS
HERE



Figure 3. Cross section of Colorado coal fly ash particles (285X).



Reproduced from
best available copy.

Figure 4. Cross section of lab prepared spent nahcolite particles (285X).

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

A sample of the coarse ground nahcolite reacted with SO_2 in a laboratory fluidized bed furnace was mounted in epoxy and polished. As discussed in the Envirotech project report (29), the reaction of sulfur dioxide with nahcolite follows predictions of an unreacted core model, where the reaction zone moves inward through the solid particulate and leaves a shell of the spent sorbent. This reaction zone on a nahcolite particle is shown in Figure 4, where there is a distinct boundary of the reddish reaction layer in contrast to the white nahcolite particle. The nahcolite used for the dry injection trials at Colorado Springs was considerably finer in particle size distribution ($< 40 \mu\text{m}$) than the laboratory-prepared particles shown in Figure 4 to increase the available surface area for a higher nahcolite utilization factor.

Figures 5 through 7 are micrographs of mounted and polished sections of fly ash/spent sorbent pellets made on a disc pelletizer and either dried at 150 C, or dried at 150 C and fired at 1000 C for 1 hour in an electrically heated furnace. All of the pellets contain fly ash and either spent nahcolite or spent trona as received from the Envirotech tests at Colorado Springs. Batch 1 contains fly ash and nahcolite, and Batch 2a has fly ash, nahcolite, and 5 percent by weight of calcium hydroxide as a pelletizing binder. Batch A contains fly ash and trona, while Batch C contains fly ash, trona, and 5 percent by weight of calcium hydroxide as a pelletizing binder. All of the pellets as dried at 150 C have distinct particle and matrix phases, while in the pellets fired at 1000 C most of the glassy particles have melted and sintered together to form a glassy matrix. Pellets fired up to 900 C show no significant evidence of melting or sintering; most of the glassy phase formation and pellet densification occurs in the range of 900 C to 1000 C.

As mentioned previously, many of the fly ash particles have a core of crystalline matter around which glass has formed during the combustion of the coal. This crystalline material is still seen in micrographs of pellets fired up to 1200 C, even though most of the glassy particles have completely melted to form a semi-continuous glassy matrix throughout the pellets. The changes in crystalline content of the pellets with thermal treatment were studied by X-ray diffraction analyses (XRD) of powder from crushed pellet samples.

The XRD results for fly ash/spent sorbent mixtures and for pellets of these compositions fired at 1000 C are shown in Table 6. Included in the table are the crystalline compounds found in the patterns, their powder diffraction file numbers, and normalized concentrations. The normalized concentrations show relative amounts of the various crystalline compounds. Best estimates for actual amounts (which are not shown in the table) would be based on factors for the ratio of crystalline to noncrystalline material in the samples. Petrographic examination of the powders indicates that roughly 50 percent of the material in both as-received and fired pellets is crystalline, indicating no substantial glass formation with thermal treatment up to 1000 C, although there has been substantial melting and sintering of the glassy particles at the higher temperatures.

An interesting difference occurs in the XRD results for the as-received powders. All of the sulfur observed in the pattern for the fly ash/spent nahcolite powder occurs as sodium sulfate, while both burkeite $[\text{Na}_6\text{SO}_3(\text{SO}_4)_2]$

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE



a. Dried at 150 C (285X)



b. Fired at 1000 C (285X)

Figure 5. Batch 1 pellet microstructure (fly ash and nahcolite).

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS



BEGIN
FIRST
LINE OF
TEXT
HERE

DROPPED
HEAD
BEGIN
SECTIONS
HERE



a. Dried at 150 C (285X)



b. Fired at 1000 C (285X)

Figure 6. Batch 2a pellet microstructure (fly ash, nahcolite, and lime).

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS



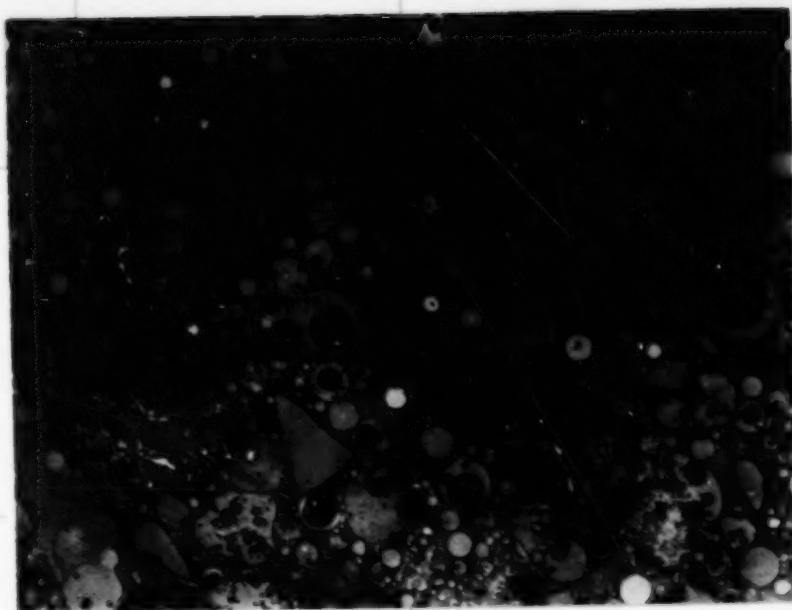
BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE



a. Dried at 150 C (285X)



b. Fired at 1000 C (285X)

Figure 7. Batch A pellet microstructures (fly ash and trona)

BEGIN
LAST LINE
OF TEXT

3/8"

25

Reproduced from
best available copy.

PAGE NUMBER

EPA-267 (Cin.)
(4-76)

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 6. X-RAY DIFFRACTION ANALYSES FOR FLY ASH/SPENT SORBENT MIXTURES

Sample	Compound	PDF No.	Normalized Concentration (Wt. Percent)
Fly ash+	α -Quartz (SiO_2)	5-490	45
Nahcolite	Mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$)	15-776	40
	Na_2SO_4 (Form III)	24-1132	6
	Natron ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$)	15-800	5
	Unknown(a)	-	2
	Magnetite (Fe_3O_4)	19-629	1
Fly ash+	Albite ($\text{NaAlSi}_3\text{O}_8$)	20-554C ^(b)	30
Nahcolite	α -Quartz (SiO_2)	5-490	28
Batch 1	Mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$)	15-776	22
Fired 1000 C	Nepheline ($\text{NaAlSi}_3\text{O}_8$)	19-1176	7
	$\text{Na}_6\text{Ca}_2\text{Al}_6\text{Si}_6\text{O}_{24}(\text{SO}_4)_2$	25-802	6
	Magnetite (Fe_3O_4)	19-629	2
	Na_2SO_4 (Form III)	24-1132	2
	Unknown	-	2
Trona+	α -Quartz (SiO_2)	5-490	35
Fly ash	Mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$)	15-776	35
Batch A	Burkeite ($\text{Na}_6\text{CO}_3(\text{SO}_4)_2$)	24-1134	18
Raw Powder	Na_2SO_4 (Form III)	24-1132	7
	Unknown	-	3
	Magnetite (Fe_3O_4)	19-629	1
Trona+	$\text{Na}_6\text{Ca}_2\text{Al}_6\text{Si}_6\text{O}_{24}(\text{SO}_4)_2$	25-802	45
Fly ash	Nepheline ($\text{NaAlSi}_3\text{O}_8$)	19-1176	18
Batch A	α -Quartz (SiO_2)	5-490	14
Fired 1000 C	Albite ($\text{NaAlSi}_3\text{O}_8$)	20-554C	8
	Mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$)	15-776	7
	Unknown	-	7
	Magnetite (Fe_3O_4)	19-629	1
Nahcolite+	$\text{Na}_6\text{Ca}_2\text{Al}_6\text{Si}_6\text{O}_{24}(\text{SO}_4)_2$	25-802	38
5% $\text{Ca}(\text{OH})_2$ +	Nepheline ($\text{NaAlSi}_3\text{O}_8$)	19-1176	25
Fly ash	α -Quartz (SiO_2)	5-490	12
Batch 2a	Unknown	-	12
Fired 1000 C	Mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$)	15-776	6
	Albite ($\text{NaAlSi}_3\text{O}_8$)	20-554C	3
	Na_2SO_4 (Form III)	24-1132	2
	Magnetite (Fe_3O_4)	19-629	1
	Anhydrite (CaSO_4)	6-226	0.4

(a) Unknown represents the intensity of the strongest unidentified line in the pattern.

(b) The C indicates a calculated pattern. This pattern gave a better fit than a pattern produced from a natural mineral specimen.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

and sodium sulfate are present in the fly ash/spent trona sample. As expected, quartz and mullite are the major crystalline Compounds in the as-received samples.

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

The complexity of the XRD patterns for the samples fired at 1000 C indicate that several new crystalline compounds are formed during thermal treatment of the pellets, while the relative amounts of quartz and mullite decrease. The most interesting and unexpected compound to form is a complex sulfate $[\text{Na}_6\text{Ca}_2\text{Al}_6\text{Si}_6\text{O}_{24}(\text{SO}_4)_2]$, which is present to some extent in all of the fired samples but is the major crystalline compound in the Batch A (trona) and Batch 2a (nahcolite plus lime) compositions. Two sodium aluminosilicate compounds (albite and nepheline) are also present in major amounts in the fired samples. The crystalline compounds present in the fired samples are a combination of small amounts of unreacted crystals (primarily quartz and mullite) and recrystallization products which form during cooling of the molten constituents.

The compounds or glasses present in the thermally treated pellets influence the degree of solubility or stability of the pellets under leaching conditions. Processing at higher temperatures (>900 C) evidently converts most of the soluble alkaline sulfates in the pellets to less soluble compounds or absorbs them partially into the glassy matrix.

Pelletizing Technique Study

The initial pelletizing experiments were conducted by pelletizing up to 2 kg of each of the fly ash/spent sorbent batches in the smaller Mars pelletizer with and without pelletizing binders added. In order to evaluate the effectiveness of the binders, the load required to rupture the pellets was measured for all of the dried pellets and for many of the pellets fired to higher temperatures (see Table 7).

The batches numbered 1 through 11 in Table 7 contain spent nahcolite sorbent while batches A, B, and C contain spent trona. Binders used included calcium hydroxide at 2 percent and 5 percent by weight, calcium lignosulfonate at 2 percent and 4 percent by weight, and bentonite at 4 percent by weight. A high calcium limestone was added to some batches because of its potential as a binder at higher sintering temperatures (as a glass network modifier and flux). These binders were tested for strength separately and in combination with other binders in the batches.

Loads required to break the dried pellets were 5 to 55 newtons (~1 to 12 pounds-force), with 15 newtons being a reasonable cut-off point below which pellets exhibited unacceptable breakage while rolling and tumbling through the various processing steps. Low dried pellet strength is also related to low green pellet strength (as discharged from the pelletizer), as measured by dropping pellets from various heights immediately after pelletizing to determine their initial resistance to breakage. The pellets with low dried strength (<15 newtons) would normally break after 1 or 2 drops from a height of 20 to 45 cm onto a hard, flat surface. Pellets with higher dried strengths usually survived multiple drops from heights up to 40

BEGIN
LAST LINE
OF

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION

3/8"

AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 7. BATCH COMPOSITIONS AND PELLET STRENGTH

Batch No.	Composition							Thermal Treatment and Load to Rupture (Newtons)							
	Flyash	Nahcolite	Trona	% Added Limestone	% Added Ca(OH ₂)	% Added Lignosulfonate	% Added Bentonite	Dried 150 °C	Fired, °C						
									700	800	900	1000	1100	1200	
1	X	X	-	-	-	-	-	5	7	11	-	-	93	-	-
2	X	X	-	5	-	-	-	17	-	-	-	-	-	-	-
2A	X	X	-	-	5	-	-	37	-	-	151	-	196	245	232
3	X	X	-	5	-	2	-	4	-	48	-	-	-	-	-
4	X	X	-	5	-	4	-	27	-	-	-	-	-	-	-
5	X	X	-	-	5	2	-	18	-	-	-	-	-	-	-
6	X	X	-	-	-	-	-	9	-	-	-	-	122	-	-
7	X	X	-	5	-	-	4	38	-	-	-	-	119	-	-
8	X	X	-	-	2	-	-	15	-	-	-	-	-	-	-
9	X	X	-	-	-	-	-	55	-	-	-	-	-	-	-
10	X	X	-	-	5	-	-	44	-	-	-	-	-	-	-
11	X	X	-	-	5	-	-	-	-	-	-	-	-	-	-
A	X	X	X	-	-	-	-	22	71	112	-	160	-	-	-
B	X	X	X	-	2	-	-	46	73	-	-	-	-	-	-
C	X	X	X	-	5	-	-	55	35	52	-	138	-	-	-

BEGIN
LAST LINE
OF TEXT

3/8"

28

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS *

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

cm. These low pellet strengths indicate that processing in shallow layers would be required to minimize breakage of pellets.

DROPPED
HEAD:
BEGIN
SECTIONS
HERE

The dried fly ash/spent nahcolite pellets broke readily with moderate handling and exhibited considerable attrition loss during handling in the sample container. Most of the binders increased pellet strength at some level of addition to the basic starting mixtures, with the spent trona batches having higher comparative dried pellet strengths than the batches containing spent nahcolite. Increases in fired pellet strength indicated some sintering and formation of glassy bonds was taking place during thermal treatment of the pellets. A 5 percent addition of calcium hydroxide $[\text{Ca}(\text{OH})_2]$ was selected for use in the larger scale pelletizing tests due to its contribution to pellet strength, comparative cost, availability, and for its possible role in the fixation of the sulfates in the mixtures. The binder also significantly reduced dusting of the pellets during handling.

Initial attempts to pelletize larger quantities of the fly ash/spent trona powder were made using the Mars Series 20 pelletizer. The pan angle was set at 73° and the pan was operated with a rim speed of 40 to 50 m/min. The powder feed rate ranged from 30 to 50 kg/hr and water flow rate was 7 to 10 l/hr. A stable condition could not be reached in this unit since the weight of the powder tumbling in the drum crushed the seed pellets.

The next attempt at pelletizing the fly ash/spent sorbent powders involved the use of the 1-meter diameter disc pelletizer. The angle was set at 60° and the rim speed was set at 70 to 80 m/min. The powder feed rate varied from 40 to 50 kg/hr while the corresponding water addition ranged from 13 to 16 l/hr. Pellets were formed readily in this pelletizer and ranged from 1 to 2 centimeters in diameter. Nearly 100 kg of pellets were made in this unit, dried at 150 C, and then sent for testing as aggregate in the concrete and asphalt mixtures. Figure 8 is a photograph of pellets made on the disc pelletizer.

Sintering Technique Optimization

Temperature and heating rate most significantly influence the amount of SO_2 evolved from the spent sorbent-containing pellets during thermal processing. The development of a glassy microstructure and/or sintering of the particles in the pellets during thermal processing influence the solubility of the pellets in a liquid. The SO_2 evolution during heat-up of pellets was measured up to 1200 C, and leaching of sodium and sulfates from pellets in water was measured after the pellets had been heated. Most of the tests were conducted on Batch 2a pellets, since this material containing spent nahcolite and 5 percent lime was considered most representative of the material that would be processed in a full-scale operating facility using a dry injection FGD process.

Figures 9 and 10 indicate the amount of SO_2 evolved from Batch 2a pellets at various temperatures and at different heating rates. Pellets heated from room temperature and held at temperatures lower than 925 C have less than 10 percent of the available SO_2 evolved during thermal processing. Above 925 C, SO_2 evolution increases more rapidly, especially at faster heating rates.

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
LAST LINE
OF TEXT



BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

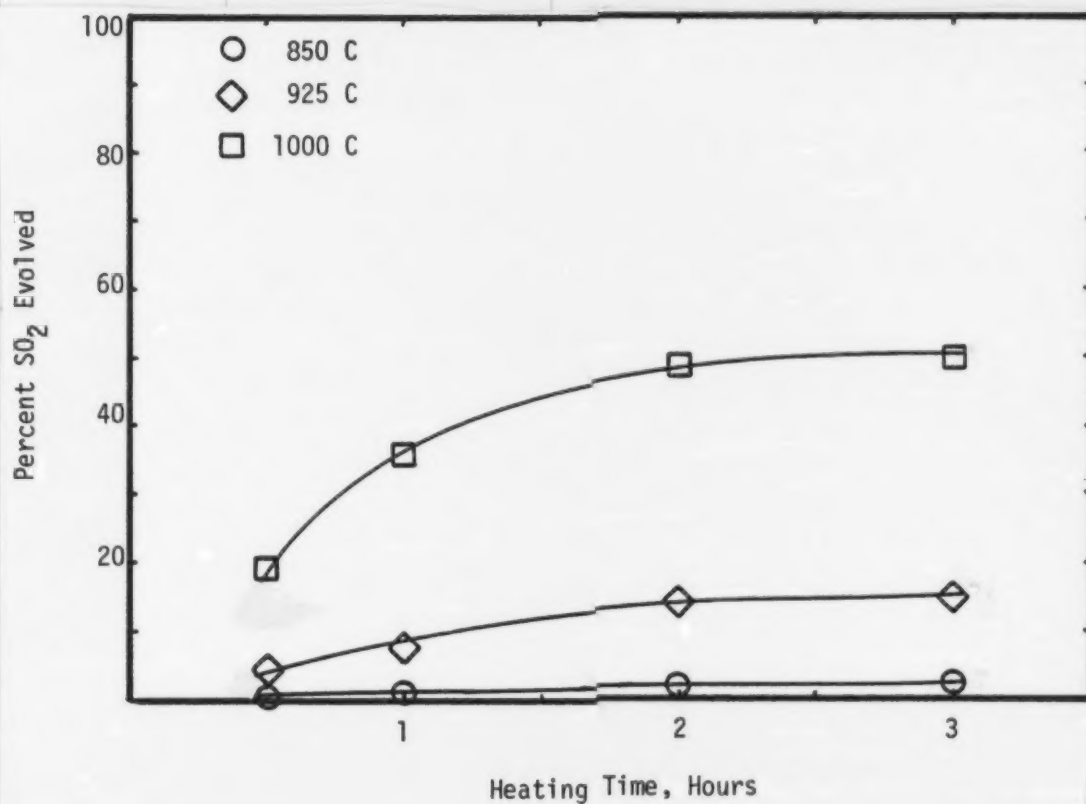


Figure 9. Percent SO₂ evolution from Batch 2a at various temperatures.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

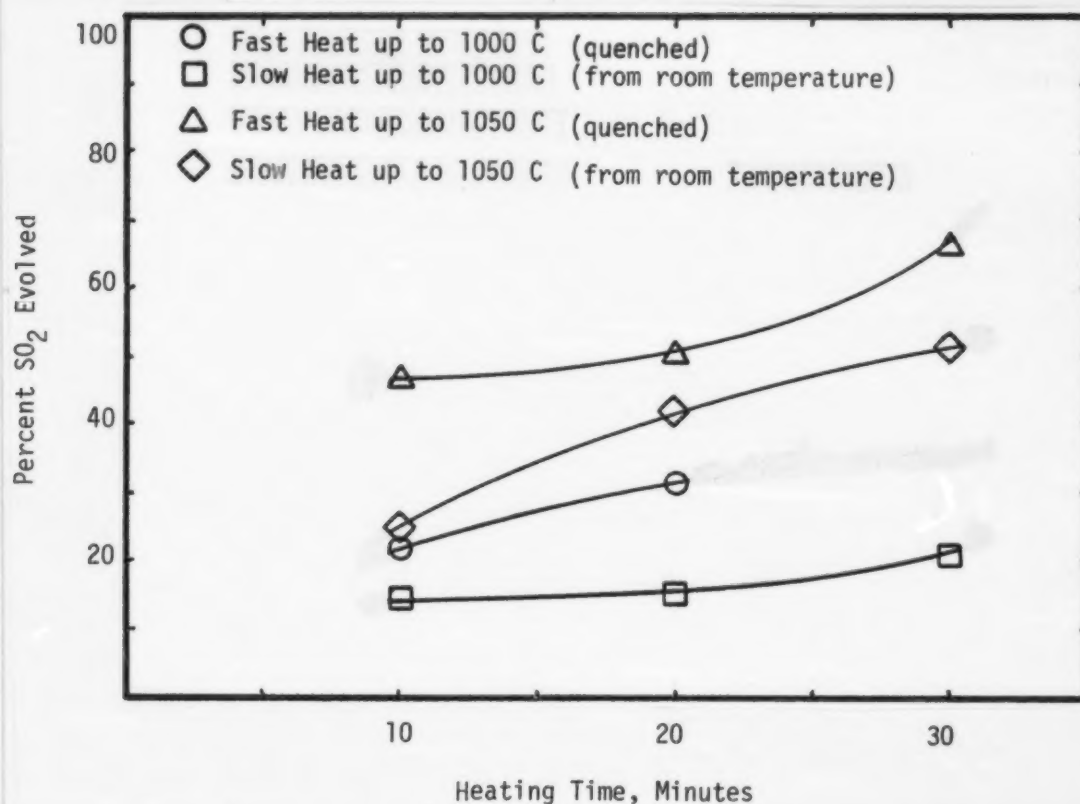


Figure 10. Effect of heating rate on SO₂ evolution from Batch 2a.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Although not shown in the graphs, essentially all of the SO_2 is evolved upon heating to 1200 C.

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

Figures 11 through 14 represent the percentages of sodium leached from pellets of four different batches which had been heated to different temperatures. As expected, the dried pellets exhibited the highest sodium leaching rates, ranging from 60 to 75 percent of the available sodium. Pellets heated to 1000 C and leached up to 100 hours had sodium leach rates ranging from 5 percent to 15 percent, indicating the stabilization of the sodium through incorporation into the glassy network.

Figures 15, 16, and 17 show the sulfate leaching behavior of Batches 2a, A, and C. In general, the sulfate leachability also decreases with increasing temperature, and the leaching rate may start to level out after 20 hours of leaching in the mildly stirred water. The overall sulfate leaching rate appears to be lowest in Batch A containing spent trona and fly ash and may depend on the type and amount of sulfate compounds present in the mixtures, the differences of which are shown in Table 6. This may also explain the difference in sulfates leached from pellets dried at 105 C, since the Batch 2a pellets containing spent nahcolite and 5 percent lime had only 60 percent of the available sulfate leached at 100 hours while the batches containing spent trona had 100 percent of the sulfate leached from them at 100 hours.

Figures 18 through 21 are composite figures which include the sulfates leached at 100 hours of stirring, SO_2 evolved after 1 hour of heating, and the calculated percentage of sulfur retained in the pellets after being subjected to both tests. By looking at the curves for total sulfur retained, the optimum temperature for thermal processing of the pellets may be determined. For Batch 1 containing fly ash and spent nahcolite, this occurs at approximately 1000 C with nearly 40 percent of the sulfur retained after testing. For Batch 2a (nahcolite plus 5 percent lime), the optimum temperature is again near 1000 C with 50 percent sulfur retention, indicating the influence of the lime addition which increased the temperature at which there was significant SO_2 evolution during thermal processing.

Batch A containing fly ash and spent trona has the overall highest sulfur retention of nearly 70 percent after heating to 1000 C. The addition of 5 percent lime to Batch A (Batch C) did not improve overall sulfur retention, but did increase the temperature at which significant SO_2 was evolved during thermal processing. Again, the differences in types and amounts of compounds present in the pellets dictate the stability of the pellets during thermal processing and under leaching conditions. Table 8 contains data from the various tests.

The leachate from several samples stirred for 100 hours was analyzed for metals by optical emission spectroscopy as shown in Table 9. The leachate from several other samples stirred for 100 hours was analyzed by inductively coupled argon plasma for increased sensitivity, as shown in Table 10. While the tables given some idea of the types of metals that would be leached from the pellets in water, the leaching tests conducted were mostly qualitative, and the test results are not to be compared quantitatively to results obtained by other researchers using tests under Resource Conservation and Recovery Act (RCRA) guidelines or the proposed ASTM leaching procedures.

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTION
HERE

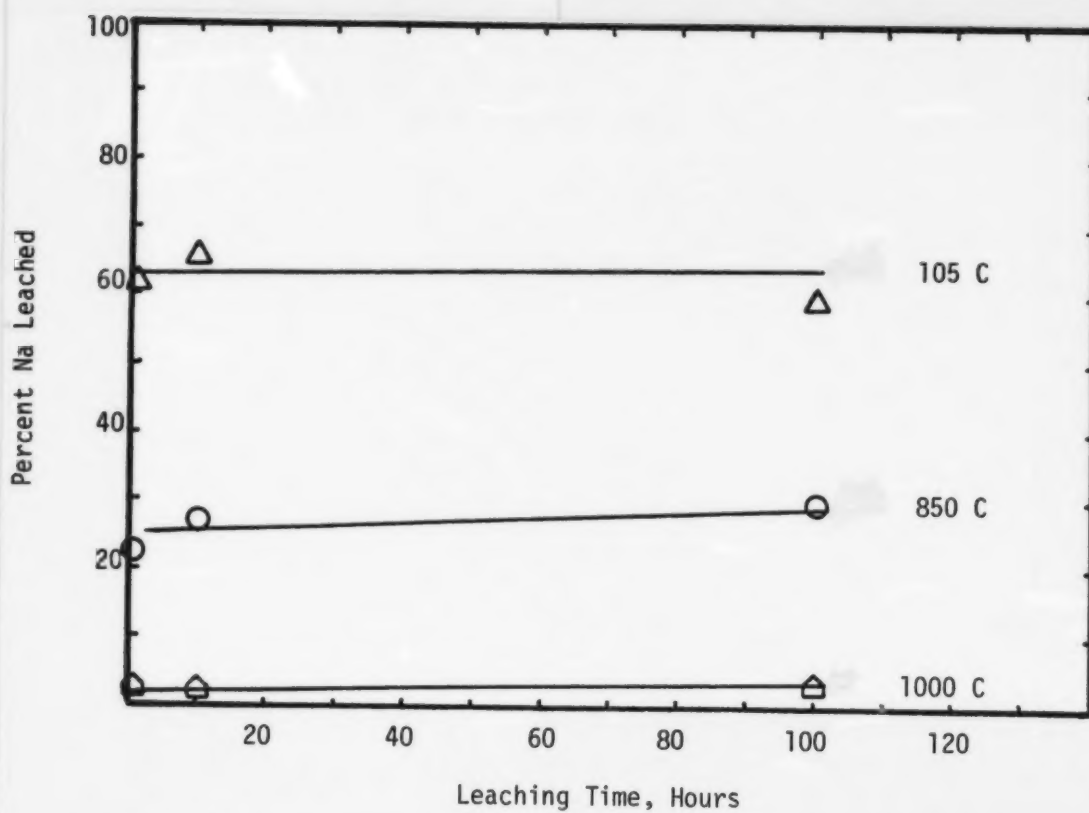


Figure 11. Percent Na leached from Batch 1 after heating at various temperatures.

BEGIN
LAST LINE
OF TEXT

3/8"

34

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

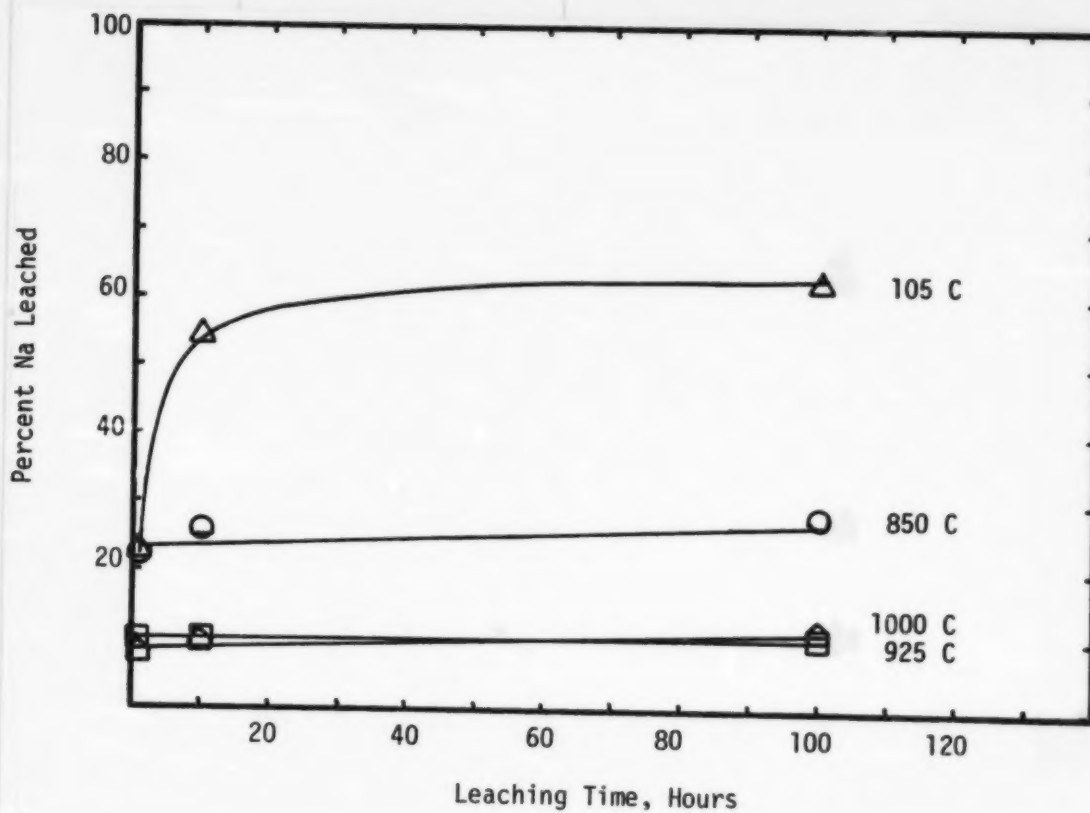
BEGIN
FIRST
LINE OF
TEXT
HEREWROPPED
HEAD
BEGIN
SECTION
HERE

Figure 12. Percent Na leached from Batch 2a after heating at various temperatures.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

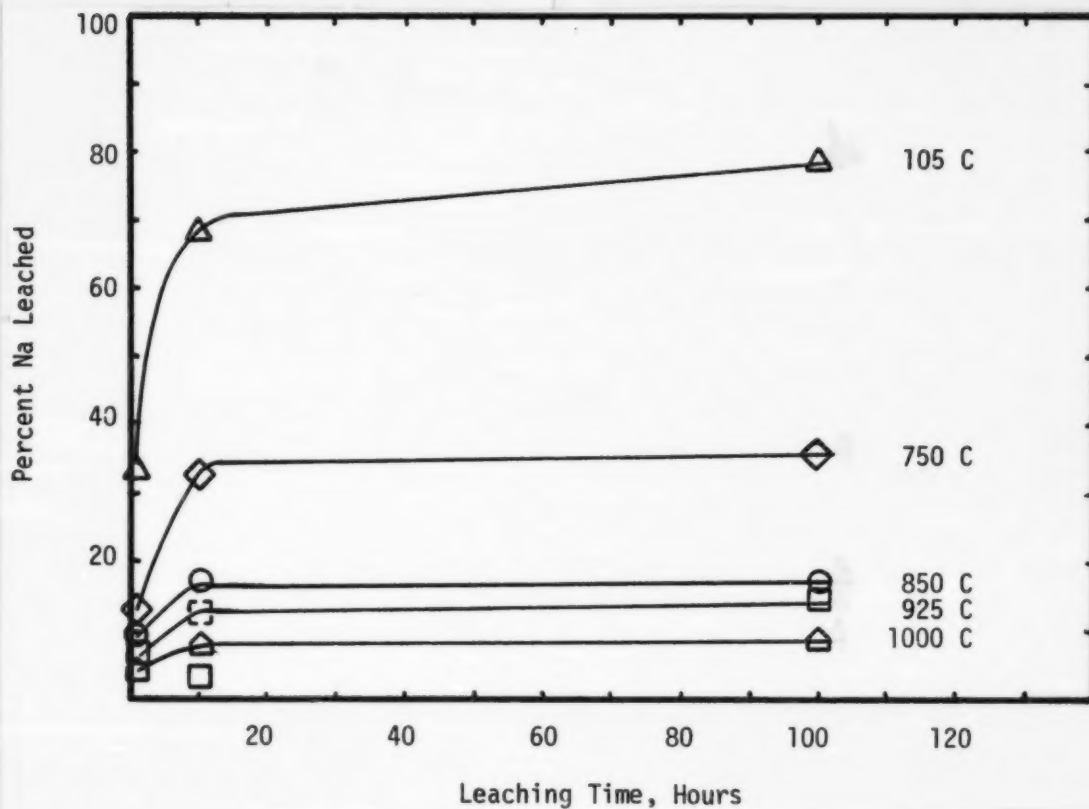


Figure 13. Percent Na leached from Batch A after heating at various temperatures.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

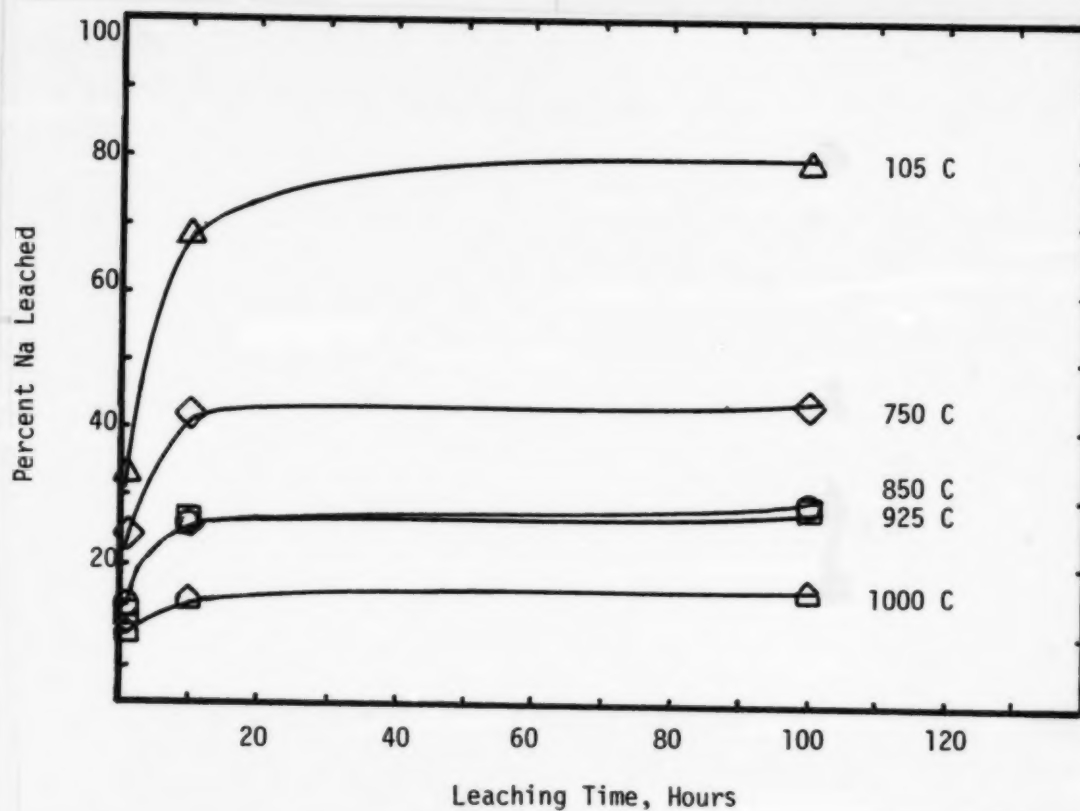


Figure 14. Percent Na leached from Batch C after heating at various temperatures.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD.
BEGIN
SECTIONS
HERE

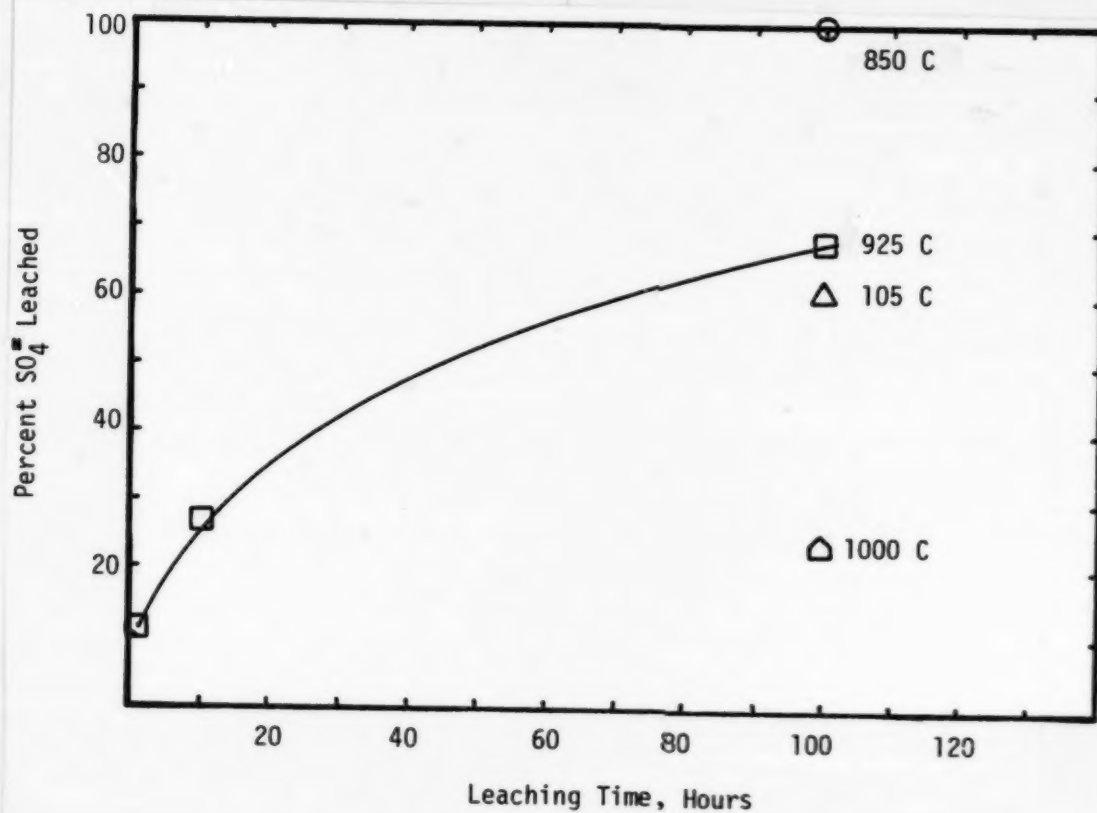


Figure 15. Percent SO_4 leached from Batch 2a after heating at various temperatures.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

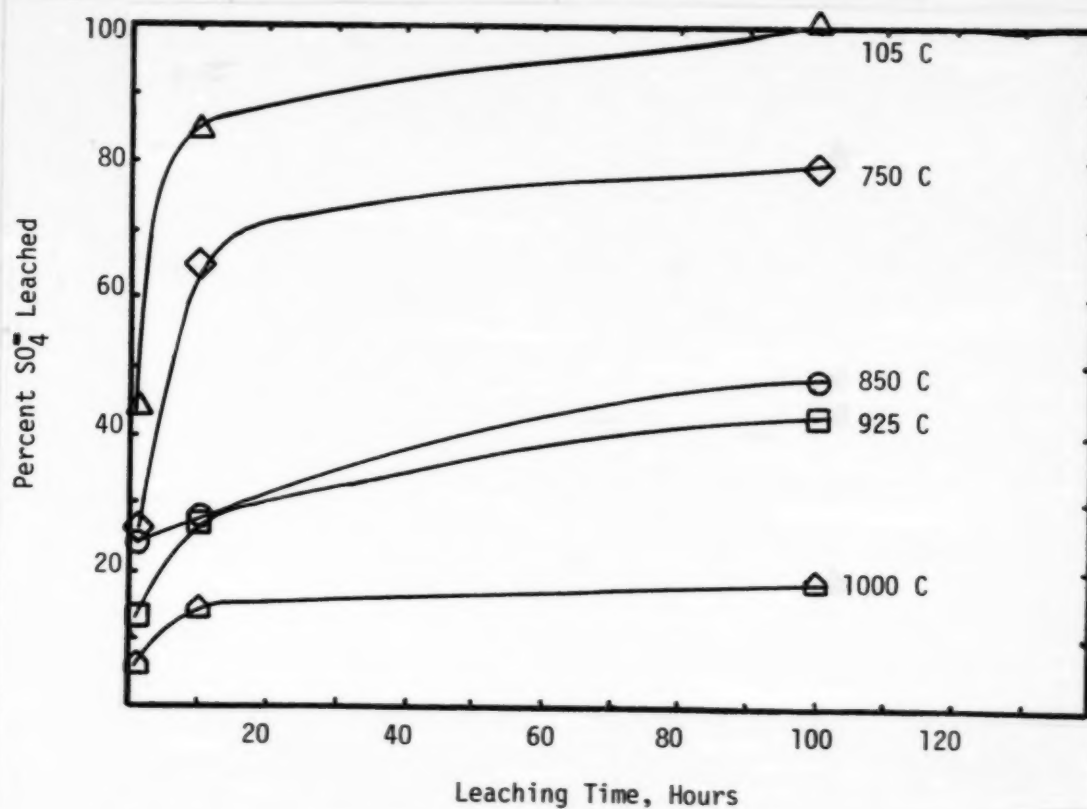


Figure 16. Percent SO_4^{2-} leached from Batch A after heating at various temperatures.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

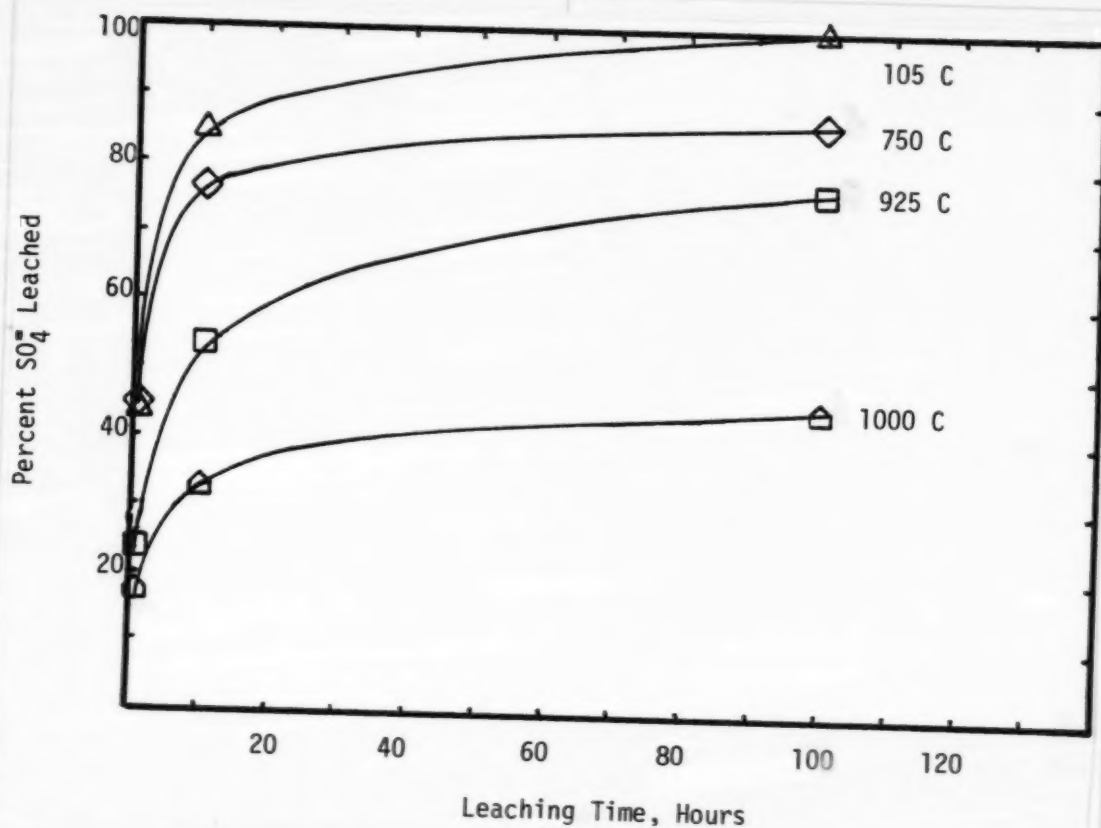


Figure 17. Percent SO_4 leached from Batch C after heating at various temperatures.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

DROPPED
HEAD
BEGIN
SECTIONS
HERE

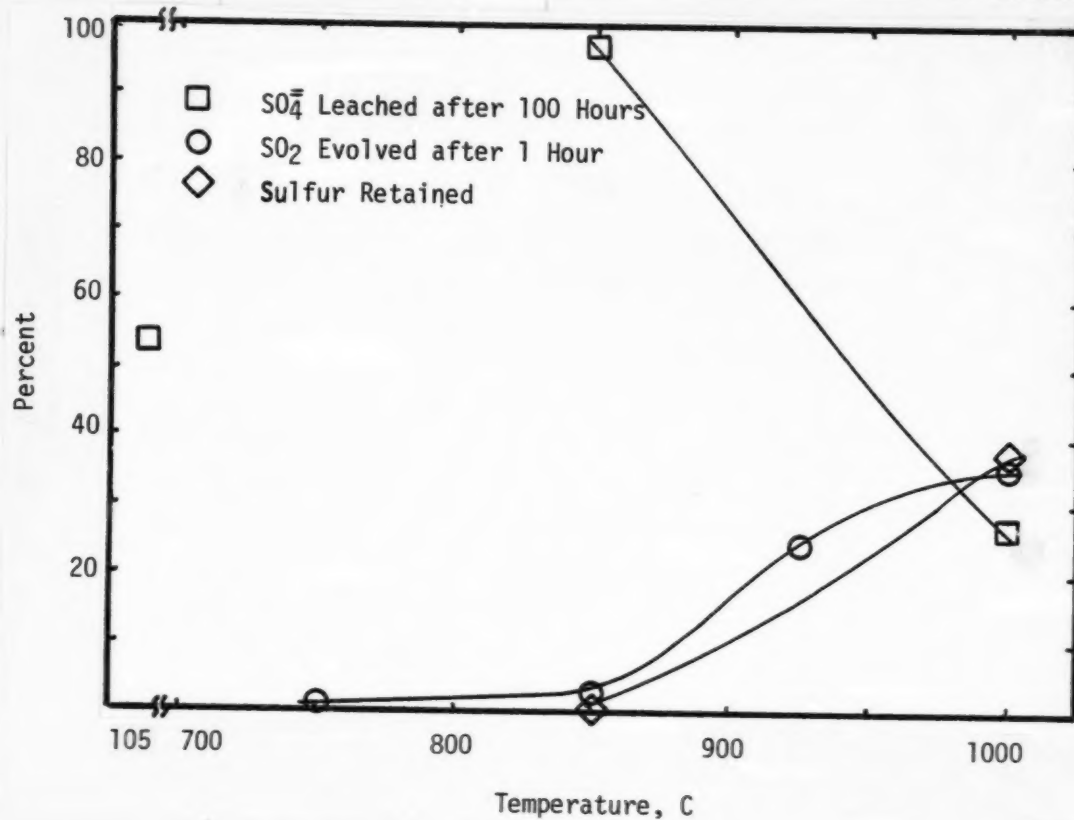


Figure 18. Sulfur retention in Batch 1 after heating and leaching tests.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

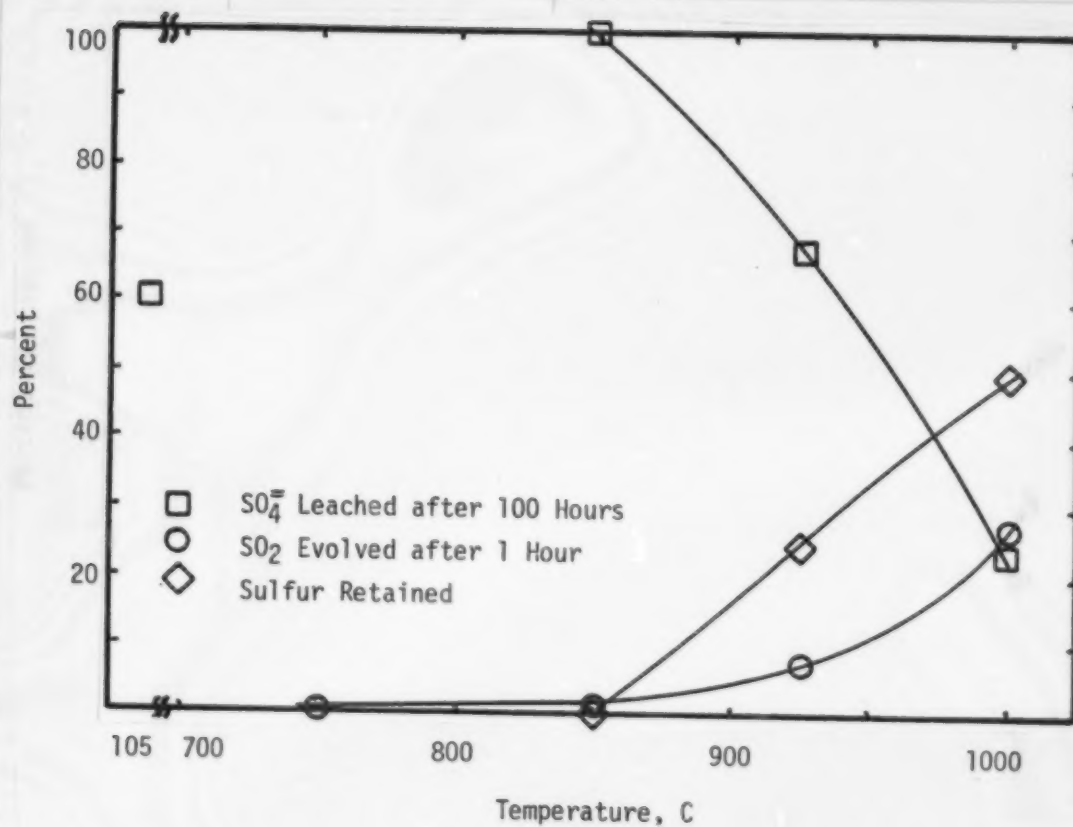
BEGIN
FIRST
LINE OF
TEXT
HEREDROPPED
HEAD
BEGIN
SECTIONS
HERE

Figure 19. Sulfur retention in Batch 2a after heating and leaching tests.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

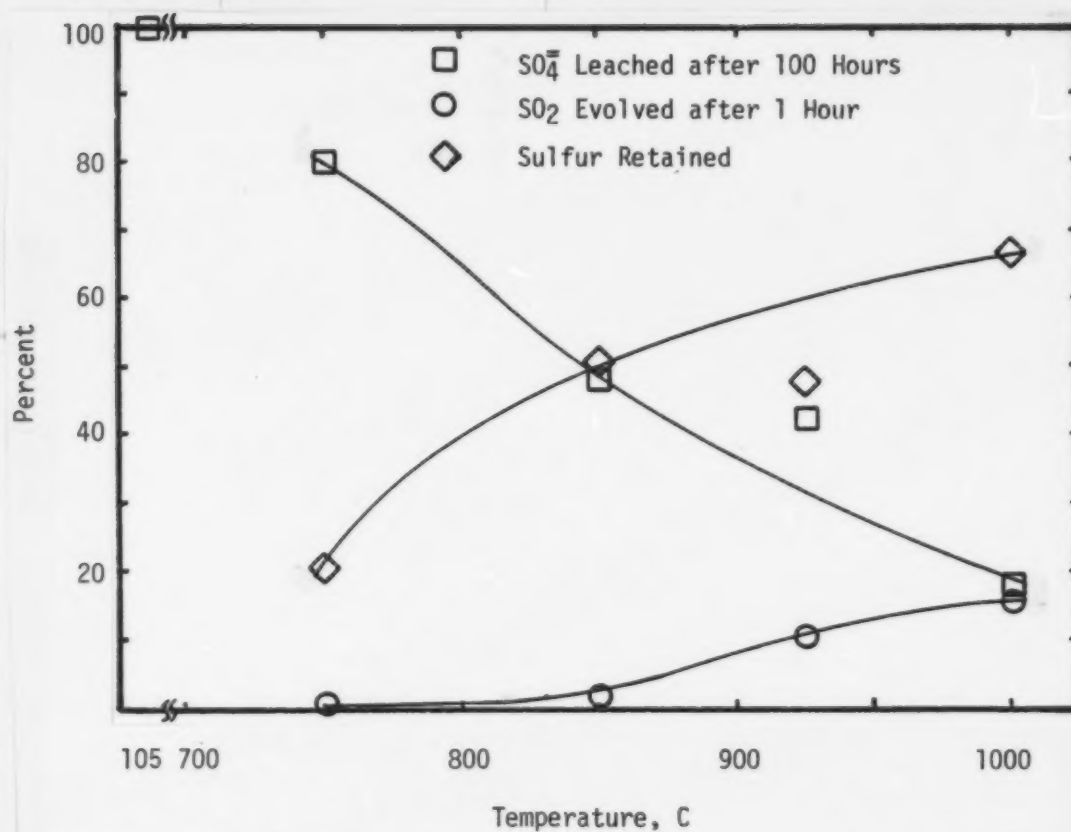
BEGIN
FIRST
LINE OF
TEXT
HEREDROPPED
HEAD:
BEGIN
SECTIONS
HERE

Figure 20. Sulfur retention in Batch A after heating and leaching tests.

BEGIN
LAST LINE
OF TEXTBOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

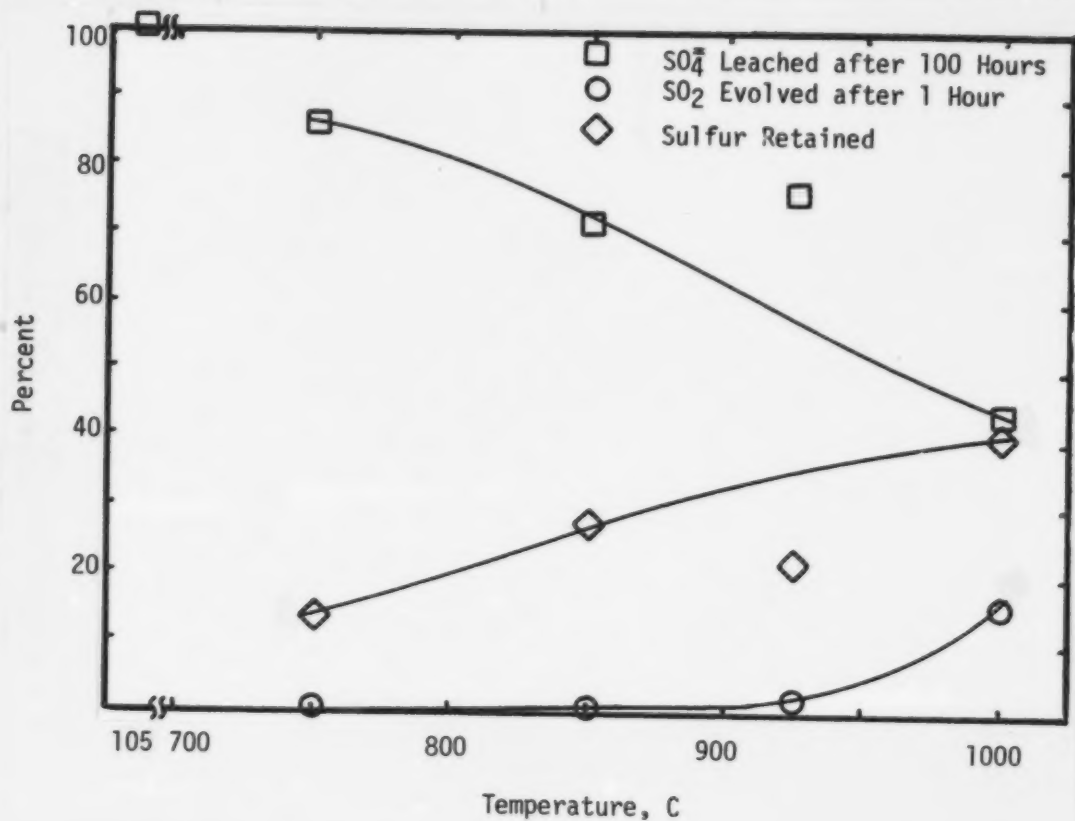


Figure 21. Sulfur retention in Batch C after heating and leaching tests.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

TABLE 8. LEACHING TEST RESULTS FOR THERMALLY TREATED PELLETS

Pellet Type(a)	Mass of Sample, Grams	Temperature of Run, C	% SO ₂ Evolved	% SO ₄ Leached			% Na Leached			% S Retained	% Na Retained
				1 Hour	10 Hours	100 Hours	1 Hour	10 Hours	100 Hours		
1	1.2050	105	-	-	-	53.8	61.8	65.0	58.4 ^(b)	46.2	41.6
1	0.9371	750	1.10	-	-	-	-	-	-	-	-
1	1.5665	850	2.90	-	-	97.2	22.0	27.1	29.3	0.0	70.7
1	1.0305	925	24.50	-	-	-	-	-	-	-	-
1	1.1057	1000	35.30	-	-	26.7	1.9	2.0	2.8	38.0	97.2
2a	0.5797	105	-	-	-	60.6	22.4	54.2	61.8	39.4	38.2
2a	0.7704	750	0.36	-	-	-	-	-	-	-	-
2a	0.9386	850	1.40	-	-	100.0	22.3	26.0	27.4	0.0	72.6
2a	0.5628	925	7.50	10.9	27.1	67.8	9.9	10.1	10.0	24.7	90.0
2a	0.9936	1000	26.90	-	-	23.5	3.1	3.5	5.3	49.6	94.7
A	0.9039	105	-	43.6	84.6	100.0	33.1	67.9	78.5	0.0	21.5
A	1.7352	750	0.46	26.0	65.3	78.9	13.1	32.8	35.5	20.6	64.5
A	1.3610	850	1.50	24.0	27.8	47.9	9.5	17.5	17.5	50.6	82.5
A	1.0728	925	10.10	13.2	27.2	42.2	6.7	3.3	14.5	47.7	85.5
A	0.9365	1000	15.20	5.7	14.0	18.1	3.8	7.7	8.5	66.7	91.5
C	0.9039	105	-	43.6	84.6	100.0	33.1	67.9	78.5	0.0	21.5
C	0.9862	750	0.40	45.0	76.5	86.2	24.6	41.9	43.6	13.4	56.4
C	0.8728	850	0.60	27.3	94.2	71.7	14.2	25.4	28.5	27.7	71.5
C	0.9113	925	1.90	23.5	53.8	76.3	12.5	25.9	28.3	21.8	71.7
C	0.7603	1000	15.70	16.9	32.5	43.9	9.8	14.4	15.9	40.4	84.1

NOTE: Pellets held at designated temperature for 1 hour.

(a) See Table 7 for compositions.

(b) Lower value due to unexplained error in testing or analysis.

BEL'IN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 9. ANALYSES OF LEACHATE FOR 100-HOUR LEACH TRIAL BY OPTICAL EMISSION SPECTRA

Batch	Thermal Treatment (C)	Elements Present (µg/ml or ppm)									
		Ba	B	Si	Fe	Mg	Al	Ca	Cu	Na	Ti
1	Dried 105	0.10	0.3	1.0	1.0	1.0	3.0	50.0*	T	50.0*	T
1	Fired 850	0.10	0.2	1.0	0.3	3.0	3.0	100.0*	T	20.0*	T
1	Fired 1000	0.05	0.4	4.0	0.5	0.5	1.0	3.0	T	<3.0	0.10
2a	Dried 105	0.05	0.3	0.5	0.4	0.5	0.5	50.0*	T	20.0*	T
2a	Fired 850	0.10	0.2	1.0	0.2	1.0	0.4	50.0*	T	3.0	T
2a	Fired 1000	0.05	0.3	3.0	3.0	0.3	0.5	3.0	T	<3.0	T

Remarks: * Estimated; Over standards
T = Trace
All other elements were sought but not detected.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

TABLE 10. METALS ANALYSIS BY INDUCTIVELY COUPLED ARGON PLASMA

Concentration Reported in Leachate, $\mu\text{g/l}$ (ppb)					
Element	Trona + Fly ash Unfired	Trona + Fly ash 1 Hour @ 925 C	Trona + Fly ash +5% Lime Unfired	Trona + Fly ash +5% Lime 1 Hour @ 925 C	Nahcolite + Fly ash +5% Lime + Extra Nahcolite 1 Hour @ 925 C
Ag	<50	<50	<50	<50	<50
Al	4360	510	3050	750	1440
As	<500	<500	<500	<500	<500
B	7740	7100	6900	5020	6080
Ba	690	850	830	820	680
Be	5	10	7	<5	5 ⁵
Ca	9860	42700	5820	55800	1.64X10 ⁵
Cd	65	110	<25	150	46
Co	<25	<25	<25	<25	<25
Cr	<50	<50	<50	190	<50
Cu	<50	180	<50	100	<50
Fe	250	<150	450	840	310
Mg	890	3770	610	730	3100
Mn	<50	<50	<50	<50	<50
Mo	97	54	66	170	58
Na	6.31X10 ⁵	1.37X10 ⁵	4.73X10 ⁵	1.60X10 ⁵	69500
Ni	<250	<250	<250	<250	<250
P	1670	<550	<550	<550	<550
Pb	<250	<250	<250	<250	<250
Sb	<500	<500	<500	<500	<500
Se	<750	<750	<750	<750	<750
Sn	<150	<150	<150	<150	<150
Sr	260	2110	72	2580	2740
Ti	<25	<25	<25	<25	<25
Tl	<1400	<1400	<1400	<1400	<1400
V	72	92	140	<25	66
Y	<25	<25	<25	<25	<25
Zn	<50	220	<50	290	<50

NOTE: Hg analysis is not possible by this method.

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Study of Pellets Used as Aggregates

DROPPED
HEAD
BEGIN
SECTIONS
HERE

The pellets used in this series of tests contained fly ash, spent nahcolite, and 5 percent hydrated lime. They were dried initially at 150 C, and nearly half of the 100 kg available was fired in an electric furnace for 1 hour at 925 C. Most of the pellets ranged in size from 5 to 9 mm in diameter, as shown previously in Table 1.

Physical properties measured on unfired and fired pellets included specific gravity and water absorption (Table 11). From these data the unfired pellets are considerably more porous than the fired pellets, although the high water absorption (37.5 percent) of the fired pellets indicates that they were not fired at a temperature high enough to achieve more complete densification through flow of the glassy phase in the pellets. One approach taken was to densify the fired pellets as much as possible to minimize leaching of the soluble constituents and to increase the strength of the pellets.

The concrete and asphalt mixes were prepared as shown previously in Table 2. The individual concrete samples were tested for compressive strength according to the ASTM C39 test procedures, and the asphalt samples were tested according to the Marshall Test Method (ASTM D1559). Table 12 shows that the samples containing spent sorbent pellets exhibited significantly lower strengths than the samples containing only the limestone aggregate. In all cases, the strength reductions are attributed to the absorbent characteristics of the pellets, as evidenced by the increases in the water-to-cement ratios for preparation of the concrete samples and higher pitch amounts in the asphalt sample mixes. The water-to-cement ratio was 0.60 for the samples with no pellets, 0.65 for the samples containing fired pellets, and 0.80 for the samples containing unfired pellets. The pitch content was 5 percent in the samples without pellets and 15 percent in both samples mixes containing pellets.

Figure 22 is a picture of fractured surfaces of concrete samples aged 28 days and broken during the compressive strength test. The sample in Figure 23 shows the relative amount of cement and limestone aggregate made from the standard mix. The sample in Figure 24 was made with a 20 percent by volume substitution of unfired pellets for the limestone aggregate, while the sample in Figure 25 has a 20 percent by volume substitution of fired pellets for the limestone. The fly ash/spent sorbent pellets bonded well to the cement matrix, as evidenced by many of the fracture cracks which have propagated through the pellets without distorting or dislodging the pellets.

Results of the sodium and sulfate leaching experiments for the concrete and asphalt samples are shown in Table 13. The sodium and sulfate values available from the fly ash/spent sorbent pellets were calculated, and the concentrations of sodium and sulfates in the leachate samples were divided by the amounts available from the pellets, after subtracting the baseline values obtained from the samples which did not contain any pellets.

BEGIN
LAST LINE
OF TEXT

The amount of sodium leached from the samples containing pellets was as high as 80 percent after 28 days for the concrete samples containing unfired

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 11. TYPICAL PROPERTIES OF FIRED AND UNFIRED
SORBENT MATERIAL (BY ASTM C-127)

	Unfired Pellets	Fired Pellets
Bulk Specific Gravity (g/cc)	0.85	1.16
Bulk Specific Gravity (g/cc) (Saturated-Surface Dry)	1.46	1.59
Apparent Specific Gravity (g/cc)	2.18	2.05
Absorption (%)	71.80	37.50

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA:
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

TABLE 12. COMPARATIVE STRENGTH RESULTS FOR CONCRETE AND ASPHALT TEST SAMPLES AFTER VARIOUS CURING PERIODS

Specimen	Compressive Strength (psi)			
	24-Hour	7-Day	14-Day	28-Day
P.C.C./#8 Limestone ^(a)	1460	3130	3770	4730
P.C.C./Unfired Pellets ^(b)	470	1490	1780	2120
P.C.C./Fired Pellets ^(c)	730	1830	2040	2520
A.C.C./#8 Limestone ^(d)	-	700	-	-
A.C.C./Unfired Pellets ^(e)	-	170	-	-
A.C.C./Fired Pellets ^(f)	-	180	-	-

P.C.C. = Portland Cement Concrete

A.C.C. = Asphalt Mix

- (a) Contained 40.0 weight percent limestone.
- (b) Contained 6.6 weight percent pellets and 32.5 weight percent limestone.
- (c) Contained 6.4 weight percent pellets and 32.5 weight percent limestone.
- (d) Contained 92.0 weight percent limestone.
- (e) Contained 13.4 weight percent pellets and 66.9 weight percent limestone.
- (f) Contained 13.1 weight percent pellets and 67.1 weight percent limestone.

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD,
BEGIN
SECTIONS
HERE

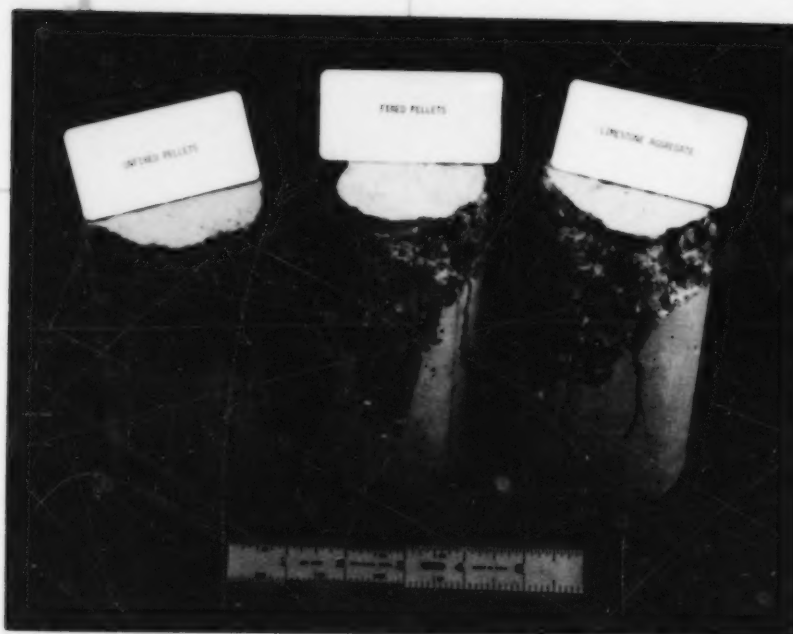


Figure 22. Fractured concrete samples.

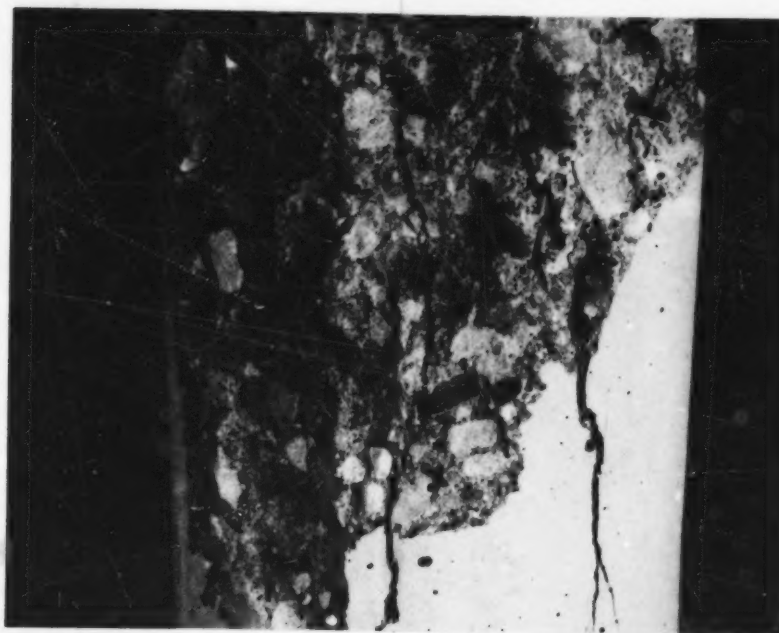


Figure 23. Concrete sample containing limestone aggregate.

BEGIN
LAST LINE
OF TEXT

3/8"

51

PAGE NUMBER

Reproduced from
best available copy.



BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE



Figure 24. Concrete sample containing unfired pellets.

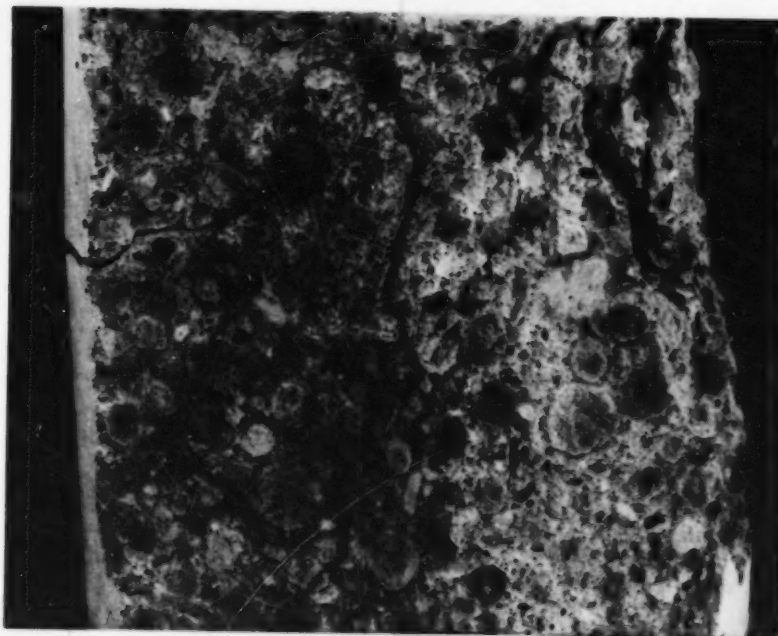


Figure 25. Concrete sample containing fired pellets.

BEGIN
LAST LINE
OF TEXT

3 1/8"

TABLE 13. SODIUM AND SULFATE LEACHING TEST RESULTS FOR CONCRETE AND ASPHALT SAMPLES

	Amount (PPM)	Sodium Leached					
		7-Day			14-Day		
		% Available	% Available Leached	Amount (PPM)	% Available	% Available Leached	Amount (PPM)
PCC/#8 Limestone	60	-	-	81.4	-	-	96.8
PCC/Unfired Pellets	676	0.117	58	867.6	0.117	74	915.3
PCC/Fired Pellets	142	0.116	12	225.6	0.116	19	271.8
ACC/#8 Limestone	8.6	-	-	10.2	-	-	12
ACC/Unfired Pellets	373.4	0.170	22	725.8	0.170	43	1013
ACC/Fired Pellets	22.4	0.170	1	47.2	0.170	3	94.8

	Amount (PPM)	Sulfates Leached					
		7-Day			14-Day		
		% Available	% Available Leached	Amount (PPM)	% Available	% Available Leached	Amount (PPM)
PCC/#8 Limestone	3.9	-	-	4.4	-	-	4
PCC/Unfired Pellets	30.1	0.137	2.2	33.7	0.137	2.4	31(a)
PCC/Fired Pellets	4.3	0.130	0.3	5.4	0.130	0.4	1.4(a)
ACC/#8 Limestone	16	-	-	27	-	-	42
ACC/Unfired Pellets	679	0.230	30	1191.8	0.230	52	1821.9
ACC/Fired Pellets	156	0.190	8	623	0.190	33	990.3

PCC = Portland Cement Concrete Mix
ACC = Asphalt Mix

NOTE: See Tables 1 and 12 for mix designs.

(a) Lower value due to unexplained error in testing or analysis.

pellets as shown in Figure 26. The asphalt samples with unfired pellets lost up to 60 percent after 28 days of leaching (of the sodium available from the pellets). The samples containing fired pellets exhibited much less leaching of the sodium available (19 percent in concrete and 3 percent in asphalt), again due to some stabilization with treatment.

The amount of sulfates leached from the asphalt samples was considerably more than that for the concrete samples containing both fired and unfired pellets, as shown in Figure 27. Nearly 80 percent of the available sulfates were leached from the 28-day asphalt sample containing unfired pellets compared with nearly 50 percent for the 28-day sample containing fired pellets. Neither of the concrete samples lost more than 2 percent of the available sulfates, presumably due to formation of less soluble calcium sulfate compounds after liberation of calcium hydroxide in the aged cement.

These results indicate that encapsulation of fly ash/spent sorbent containing pellets in concrete or asphalt does not significantly inhibit the leaching in water of soluble compounds from the pellets. In order to minimize the leaching behavior of the pellets, they must be thermally processed at the optimum temperature and rate as suggested by Figures 18, 19, 20, and 21 for total sulfur retention (presented previously in the section on sintering).

Process Flow Sheet

The processing of the fly ash/spent sorbent-containing powder from a power plant baghouse by the Sinterna process is based on agglomeration of the powder into some form suitable for sintering in a furnace capable of handling the projected output of material. For a 500 MW power plant, the fly ash collected was calculated at 17.6 tonnes per hour, based on coal burned at a rate of 227 tonnes per hour. This coal is described as a low sulfur (0.7 percent) western coal with 9.7 percent ash and a heating value of 9700 Btu/lb. Eighty percent of the coal ash is presumed to be collected as fly ash.

The basic process flow diagram is as shown in Figure 28. The core of the process consists of two 5-meter (diameter) disc pelletizing units which would each handle over 20 tonnes per hour of powdered material from the baghouses and recycled material from the screens and sintering furnace. Nearly 20 percent water by weight is required to pelletize the material. After screening into the desired size distribution, the pellets are conveyed into a traveling grate sintering furnace with multiple compartments for drying, sintering, and cooling the pellets. An estimated 40 percent of the pelletizer output would be recycled after being rejected from the screening and sintering operations. Other material flows are shown in Table 14.

Prior to feeding the powder into the pelletizer, a binder such as hydrated or burned lime could be added in a screw-type conditioning unit. The recycled material could also be mixed into the main feed stream at this point.

After passing over or through classification screens, the wet pellets enter the drying section of the traveling grate furnace which precedes the sintering zone shown in Figure 29. As furnaces vary considerably in design, function, and output rate, the furnace size estimates used here are based on

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

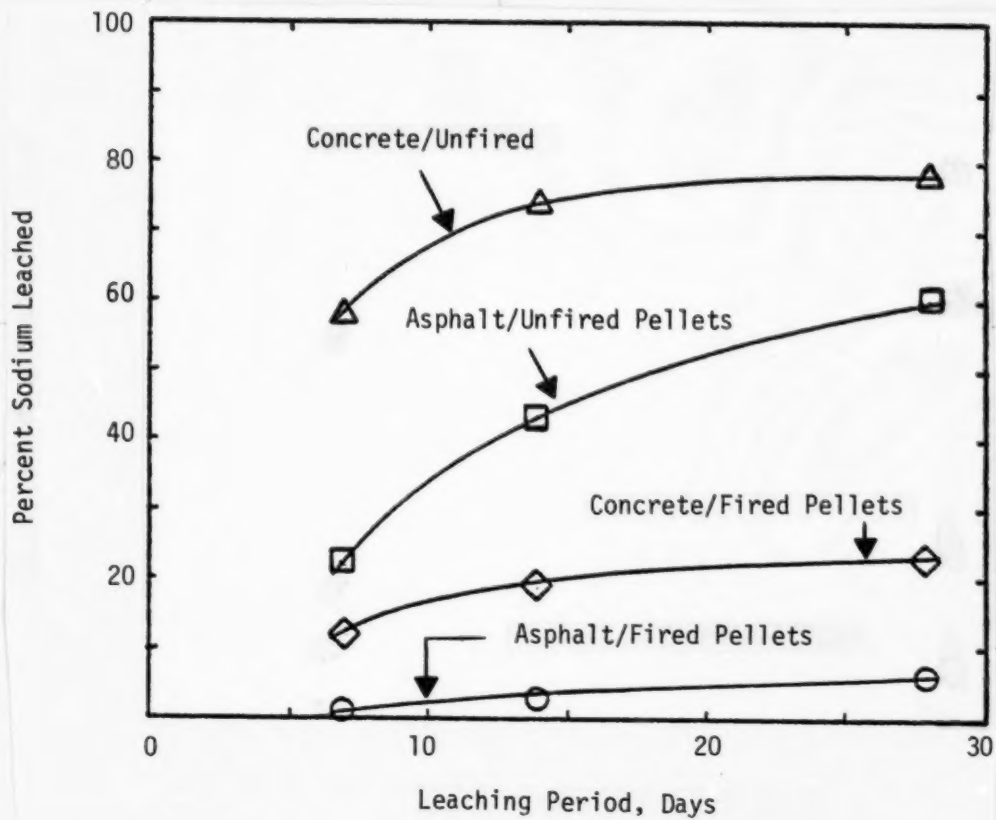


Figure 26. Sodium leached from concrete and asphalt samples.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

CHOPPED
HEAD
BEGIN
SECTIONS
HERE

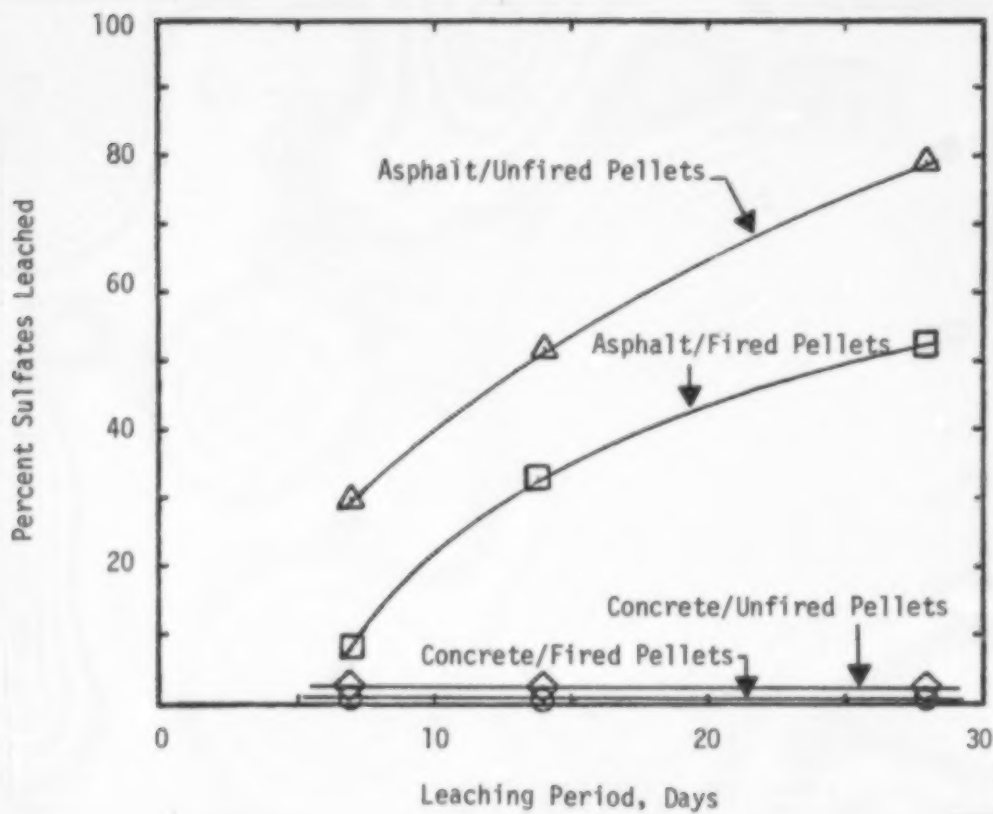


Figure 27. Sulfates leached from concrete and asphalt samples.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD.
BEGIN
SECTIONS
HERE

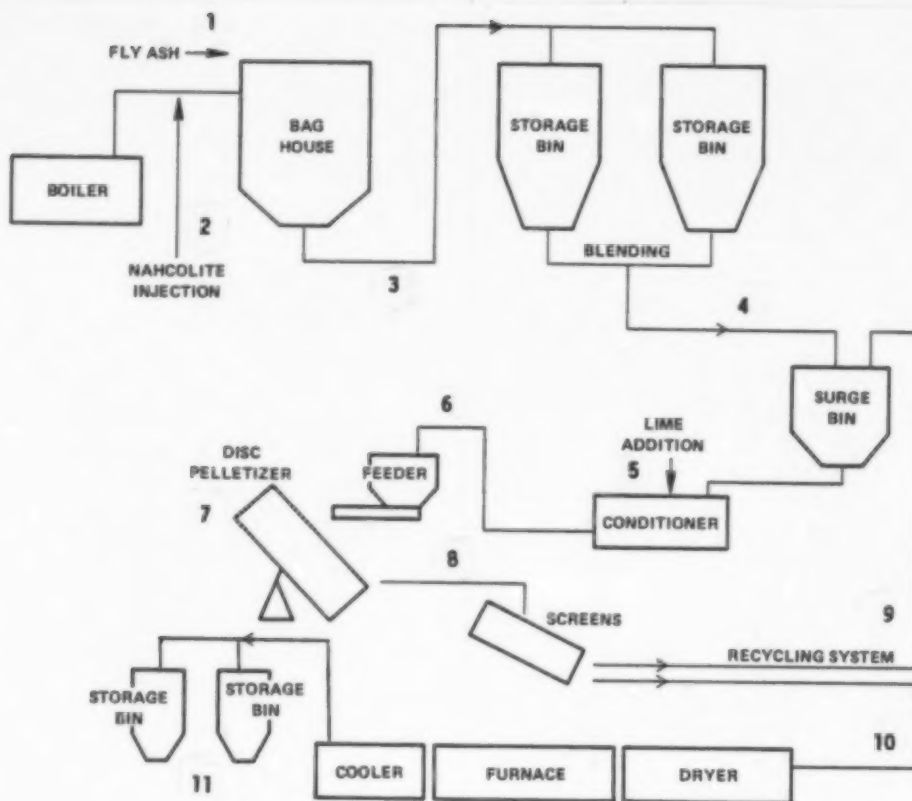


Figure 28. Process flow diagram.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 14. MATERIAL FLOWS IN THE PROCESS FLOW DIAGRAM

Stream Number	Material Flow Rate (tonnes/hr)	Material Description
1	17.2	Fly Ash
2	7.3	Nahcolite
3	24.5	Fly Ash/Nahcolite
4	24.5	Fly Ash/Nahcolite
5	1.3	Lime
6	41.5	Fly Ash/Nahcolite/Lime
7	8.2 (8.2 kL/hr)	Water
8	49.0	Wet Pellets
9	15.7	Broken Pellets
10	33.3	Wet Pellets
11	25.1	Fired Pellets

- NOTES: (1) Binder and SO₂ weight losses are negligible.
 (2) Sintering unit waste was considered in recycling system.
 (3) Natural gas in stream 10 (Fig. 28) is 25,000 ft³/hr. Other gases are not considered.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

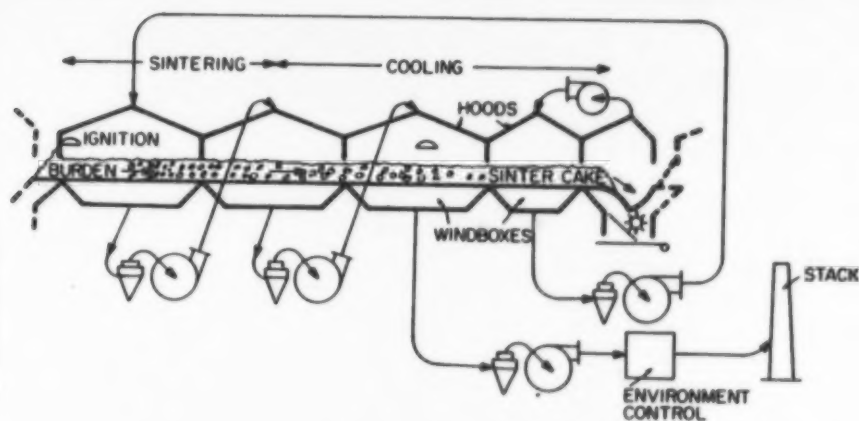
TYPING GUIDE SHEET

BEGIN
FIRST
LINE OF
TEXT
HERE

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE



Source: Reference 17

Figure 29. Traveling grate sintering process.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTION
HERE

conservative processing factors and on information available in the literature for processing of similar types of materials. The size of the furnace grate was estimated at 3 meters wide by 54.5 meters long. Based on a material processing estimate of $1.5 \text{ m}^3/\text{m}^2\text{-hour}$, this furnace would handle the desired output of 24 to 45 tons/hour from the pelletizing units. The sintered pellets are discharged to storage bins or stockpiles until removal from the power plant site. It should be noted that units of this size in the iron ore industry are capable of handling 2 to 3 times the amount of material projected for this application, but special consideration has been made for the careful control of the processing conditions to yield stabilized pellets without a significant loss of SO_2 from the spent sorbent.

The sintering unit could not be operated in the same manner as those units used for making fly ash pellets into lightweight aggregate. The lightweight aggregate process depends on burning of the nearly 3 percent carbon in the pellets to control the sintering rate in the firing zone of the furnace which forms gases causing an increase in porosity in pellets and a decrease in pellet density. The fly ash/spent sorbent mixtures used in this study contained less than 1 percent carbon. This low carbon content is desirable since carbon reacts with sulfates in the sintering temperature range to release SO_2 prematurely from the pellets, contrary to the intended purpose of sintering the pellets.

The gases exiting the cooling end of the sintering grate furnace should most likely be recycled back into the boiler flue prior to the point where the dry nahcolite or other sorbent would be injected, since some SO_2 would be released in the sintering process. Using a normal figure of 2.5 kg of gas per kg of solids per pass through the sintering grate, the gas volume to be recycled would constitute less than 10 percent of the total gas volume in the flue. This gas recycling was not included in our material balances for the process flow diagram, but it would affect the amount of sorbent required to handle the increased amount of SO_2 in the flue gases. A larger baghouse may also be needed to handle the increased volume of gases. The cost of the extra sorbent and larger baghouse would be allocated to the sintering process.

One other assumption made about the operation of the pelletizing and sintering facility is that it would be operating 5500 hours per year and at the same times the boiler would be in operation. Although this would not be a realistic practice, the assumption was made to facilitate calculation of estimated annual operating costs. A complete and accurate materials balance sheet could only be completed with additional process information which is not currently available, but much process data would be needed for designing the sintering unit.

Table 15 is a more complete listing of the major process equipment, estimated installed cost in 1982 dollars, and estimated electricity usage for annual cost calculations for this equipment. Other utilities used are listed in Table 17. The total process equipment costs are estimated at \$7,102,000, and total factored capital costs for the processing facilities are shown in the next section of the report.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

TABLE 15. SPENT SORBENT FIXATION PROCESS EQUIPMENT LIST,
INSTALLED COST, AND ELECTRICITY USAGE

Area 1--Material Handling

Item	No.	Total Installed Cost, 1982 \$	Electricity Usage, kWh/hr
1. Conveyor, pneumatic, from baghouse to bins	1	114,000	56
2. Dust collector	2	40,000	11
3. Silo, 500 ton ash storage	2	440,000	7.5
4. Silo, 50 ton lime storage	1	45,000	1.5
5. Conveyor, blended ash	1	28,000	1.9
6. Silo, ash surge capacity	1	21,000	1.5
7. Conveyor, lime feed	1	8,000	1.5
Subtotal		696,000	80.9

Area 2--Agglomeration

Item	No.	Total Installed Cost, 1982 \$	Electricity Usage, kWh/hr
1. Conditioner, pelletizer feed	2	78,000	60
2. Conveyor, pelletizer feed	2	34,000	3
3. Feeder, pelletizer	2	74,000	5.3
4. Dust collector, pelletizers	2	40,000	11.3

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 15. (Continued)

Area 2--Agglomeration

Item	No.	Total Installed Cost, 1982 \$	Electricity Usage, kWh/hr
5. Pelletizer, 5 meter diameter	2	210,000	90
6. Conveyor, green pellets	2	34,000	3
7. Screens, pellet classi- fication	2	30,000	7.5
8. Recycling system, conveyors for off-size pellets	2	66,000	7.5
9. Crusher, recycled pellets	1	<u>333,000</u>	<u>75</u>
Subtotal		899,000	269.6

Area 3--Sintering

Item	No.	Total Installed Cost, 1982 \$	Electricity Usage, kWh/hr
1. Hopper, feed unit for dryer	1	50,000	0.8
2. Grate furnace, dryer, kiln, cooler, fans, dust collectors	1	5,000,000	3,000
3. Conveyor, to finished product storage	1	<u>17,000</u>	<u>1.5</u>
Subtotal		5,067,000	3002.3

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 15. (Continued)

Area 4-- Product Storage

Index	No.	Total Installed Cost, 1982 \$	Electricity Usage, kWh/hr
1. Silos, finished product storage	2	<u>440,000</u>	<u>7.5</u>
Subtotal		440,000	7.5
Total Process Equipment		7,102,000	3,400

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

Economic Analysis

DROPPED
HEAD
BEGIN
SECTIONS
HERE

As shown in the previous section, the estimated total process capital for the spent sorbent fixation process is \$7,102,000. The remaining factored capital costs are presented in Table 16. Total direct investment is \$11,789,000, and by adding the indirect investment costs, the total fixed investment costs are \$16,858,000. Addition of the various other capital charges shown in the table makes the total capital investment for the process to be \$20,277,000. This is equal to \$40.55 of total capital per kW of generation capacity for the 500 MW plant.

Annual revenue requirements for the spent sorbent fixation process are shown in Table 17. These consist of direct operating and maintenance costs of \$4,662,490, plus \$924,636 in overhead costs for a total of \$5,587,126 in total first-year operating and maintenance costs. By adding in the levelized capital charges at 14.7 percent of the total capital investment, the total first-year revenue requirements are \$8,567,845 (or 3.12 mills/kWh). The levelized operating and maintenance costs are \$10,537,319. Adding the levelized capital charges to this sum, the levelized annual revenue requirements are \$13,518,038 (or 4.92 mills/kWh) over the 30-year plant life.

Based on waste disposal of 154,190 tonnes per year (ash plus spent sorbent), the levelized annual cost of waste fixation is nearly \$88 per tonne of waste, or \$10 per ton of coal burned. Based on 0.7 percent sulfur coal, this cost is over \$1,400 per ton of sulfur removed. Since these costs are based on a very conservative estimate of throughput for the process, they are felt to be worst case estimates and in actuality could be much lower. However, it should be noted that these costs do not include SO₂ removal from gases leaving the furnace. Removal of this evolved SO₂ from the heated pellets would entail added capital and operating costs for the plant FGD system.

Since nearly 45 percent of the total capital costs are derived from the sintering unit and building and site development, greater utilization of these facilities would lower the unit costs for the process. This could be accomplished by increasing the furnace load factor by processing material from other power plants in the same region, or by stockpiling and processing waste material from mines or industrial processes. The costs estimated here are much higher than originally anticipated, and probably unacceptable in view of alternative waste disposal options (landfilling in isolated cells and absorbent regeneration with calcium compounds).

DISCUSSION

From a technical standpoint, the results of this program are mixed in terms of feasibility or desirability of using a Sinterna-type process for disposal of fly ash/spent sodium compound mixtures from dry FGD systems. From an economic standpoint, the process appears to be too costly for disposal of the FGD by-products from a single 500 MW power plant.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA,
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTION
HERE

TABLE 16. SPENT SORBENT FIXATION PROCESS

TOTAL CAPITAL INVESTMENT

(500-MW new coal-fired power unit, 0.7% in coal;
70% SO₂ removal; onsite solids disposal)

<u>Direct Investment</u>	<u>Investment, k\$</u>
Material handling	696
Agglomeration	899
Sintering	5,067
Product Storage	440
Total process capital	7,102
Building and site development	4,261
Services, utilities, and miscellaneous	426
Total Direct Investment	11,789
<u>Indirect Investment</u>	
Engineering design and supervision	825
Architect and engineering contractor	236
Construction expense	1,886
Contractor fees	589
Contingency	1,533
Total Fixed Investment	16,858
<u>Other capital charges</u>	
Allowance for startup and modification	1,179
Interest during construction	1,839
Working capital	401
Total Capital Investment	20,277
Dollars of total capital per kW of generation capacity	40.55

Basis

Great Plains-Rocky Mountains plant location represents project beginning mid-1981, ending mid-1983. Average cost basis for scaling, mid-1982.

BEGIN
LAST LINE
OF TEXT

3/8"

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

TABLE 17. SPENT SORBENT FIXATION PROCESS

ANNUAL REVENUE REQUIREMENTS

(500-MW new coal-fired power unit; 0.7% S in coal;
70% SO₂ removal; onsite solids disposal)

Direct Costs - First-Year	Annual Quantity	Unit Cost, \$	Total Annual Cost, \$
Raw Materials			
Hydrated lime	5500 tons	150/ton	825,000
Total raw materials cost			825,000
Conversion Costs			
Operating labor and supervision	24,090 man-hr	15.00/man-hr	361,000
Utilities			
Process water	14,047 kgal	0.14/kgal	1,967
Electricity	18,700,000 kWh	0.037/kWh	691,900
Natural gas	457,875 k ft ³	3.50/k ft ³	1,602,563
Maintenance			1,180,060
Total conversion costs			3,837,490
Total direct costs			4,662,490
Indirect costs - First-Year			
Overheads			
Plant and administrative (60% of conversion costs less utilities)			924,636
Total first-year operating and maintenance costs			5,587,126
Levelized capital charges (14.7% of total capital investment)			2,980,719
Total first-year annual revenue requirements			8,567,845
Levelized first-year operating and maintenance costs (1.886 first-year 0 and M)			10,537,319
Levelized annual revenue requirements			13,518,038
	<u>M\$</u>	<u>Mills/kWh</u>	
First-year annual revenue requirements	8.57	3.12	
Levelized annual revenue requirements	13.52	4.92	

Basis

Great Plains-Rocky Mountains plant location, 1984 revenue requirements.
Remaining life of power plant, 30 years.
Power unit on-stream time, 5,500 hr/yr.
Coal burned, 1,347,000 tons/yr; 9,700 Btu/lb.
Total direct investment, \$11,789,000; total fixed investment, \$16,858,000; and total capital
investment, \$20,277,000.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLU-
STRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
SECTION
HERE

DROPPED
HEAD
BEGIN
SECTION
HERE

The fly ash/spent sorbent powders can be agglomerated by disc pelletizing methods using small amounts of a binder such as hydrated lime to improve pellet strength. These pellets containing soluble alkali sulfates can be sintered at temperatures up to approximately 1000 C to minimize their solubility in water. However, with a processing temperature above 900 C, the amount of SO₂ evolved from the pellets increases substantially with increasing temperature. After heating and leaching trials on pellet samples, 30 percent to 60 percent of the total sulfur in the pellets was either evolved as SO₂ during the heating or leached out as sulfate in water. The impact on baghouse size and sorbent usage of recycling the SO₂ evolved back into the ductwork to be treated again needs to be investigated further, since it will add to the estimated costs. Also, a more thorough characterization of the amount and type of leachates from these materials anticipated under actual conditions must be conducted according to federal guidelines.

Initial speculation that the sintered pellets could be used as aggregates in concrete and bituminous mixes was somewhat dampened by test results which indicated significant decreases in strength for mixes containing either fired or unfired pellets. Also, encapsulation of the pellets in the concrete and bituminous mixes did not prevent substantial leaching of the soluble compounds in the pellets.

The high capital cost of this venture (>\$20 million) is driven primarily by the high cost of a sophisticated sintering machine, which results in a high levelized annual revenue requirement (4.92 mills/kWh) after allocation of the fixed costs.

The technical considerations and economic comparisons to alternative FGD systems would indicate that the Sinterna process, as considered and described in this report, is not entirely desirable or recommended for adoption at the present time. The dry FGD process using nahcolite or trona as a sorbent, however, has high merits and should not be discounted based on the findings in this report. Some less costly alternative method of disposal of the soluble fly ash/spent sorbent materials is obviously required, and further research is required to identify promising alternatives.

Suggested alternative disposal methods might include disposal in lined disposal pits with controlled run-off, or processing of the material removed from the baghouse by methods similar to a double alkali process, where the spent sorbent would be dissolved in water, then reacted with lime and converted to gypsum. Feasibility and cost estimates for these alternatives might be gained through analysis of similar existing systems.

BEGIN
LAST LINE
OF TEXT

3/8"

67

PAGE NUMBER

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD;
BEGIN
SECTIONS
HERE

REFERENCES

1. Burnett, T. A. and O'Brien, W. E., "Preliminary Economic Analysis of a Lime Spray Dryer FGD System," EPA-600/7-80-050, U. S. Environmental Protection Agency (March, 1980).
2. Bennett, R. B., Rosenberg, H. S., and Genco, J. M., "Insolubilization of Spent Sorbent Alkali Ores Used for Desulfurizing Flue Gases," Report to Industrial Resources, Inc. by Battelle's Columbus Laboratories (January 24, 1975).
3. Brownell, W. E., "Fundamental Factors Influencing Efflorescence of Clay Products," Journal of the American Ceramic Society, 32 (12), pp. 375-389 (1949).
4. Brownell, W. E., "Know the Fundamentals to Control Efflorescence," Brick and Clay Record, 116 (1), pp. 68-70 (1950).
5. Brownell, W. E., "Efflorescence Resulting from Sulfates in Clay Raw Materials," Journal of the American Ceramic Society, 41 (8), pp. 310-314 (1958).
6. Pearce, M. L. and Beisler, J. F., "Miscibility Gap in the System Sodium Oxide-Silica-Sodium Sulfate at 1200 C," Journal of the American Ceramic Society, 48 (1), pp. 40-42 (1965).
7. Torrey, S., Editor, Coal Ash Utilization-Fly Ash, Bottom Ash and Slag, Noyes Data Corporation, Park Ridge, New Jersey (1978).
8. Mitchell, R. I. and Baytos, W. C., "Collection and Analyses of Fly Ash from Stack Gas Emissions," Report to the U. S. Environmental Protection Agency under Contract No. 68-03-1371 by Battelle's Columbus Laboratories (February 1, 1979).
9. Ray, S. S. and Parker, F. G., "Characterization of Ash from Coal-Fired Power Plant", EPA-600/7-77-010, U. S. Environmental Protection Agency (January, 1977).
10. Faber, J. H. et al., Ash Utilization Proceedings of the Fourth International Ash Utilization Symposium, St. Louis, Missouri (March, 1976), NTIS MERC/SP-76/4.
11. Dulin, J. M. et al., "Sodium Sulfur Oxides Wastes Disposal Process," U. S. Patent No. 3,962,080 (June 8, 1976).

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA;
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

68

PAGE NUMBER

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD
BEGIN
SECTIONS
HERE

REFERENCES
(Continued)

12. Minnick, L. J., Webster, W. C., and Smith, C. L., "Lime-Fly Ash-Sulfite Mixtures," U. S. Patent No. 3,785,840 (January 15, 1974).
13. Messman, H. C. and Tibbet, T. E., Editors, Elements of Briquetting and Agglomeration, Institute for Briquetting and Agglomeration. Waterloo, Ontario, Canada (1977), pp. 47-54.
14. Gruver, R. M., "Differential Thermal-Analysis Studies of Ceramic Materials:III, Characteristic Heat Effects of Some Sulfates," Journal of the American Ceramic Society, 34 (11), pp. 353-357 (1951).
15. Spencer, J. D. and Whieldon, C. E., Jr. Editors, Fifth International Ash Utilization Symposium Proceedings, U. S. Department of Energy, Morgantown, West Virginia (February, 1979), METC/SP-79/10.
16. Shannon, D. G. and Fine, L. O., "Cation Solubilities of Lignite Fly Ashes," Environmental Science and Technique, 8 (12), pp. 1026-1028 (1974).
17. Rose, J. G. and Stewart, O. W., "Use of an Improved Continuous Sintering Grate for Lightweight Aggregate Production from Bituminous Coal Refuse," in Proceedings of Fifteenth Biennial Conference, The Institute of Briquetting and Agglomeration, Montreal, Quebec (1977), pp. 41-56.
18. Blythe, G. M. and Dickerman, J. C., "Survey of Dry SO₂ Control Systems," EPA-600/7-80-030, U. S. Environmental Protection Agency (February, 1980).
19. Organization for Economic Cooperation and Development, Road Research, "Use of Waste Materials and By-Products in Road Construction" (September, 1977).
20. Weismantel, G. E., "Ash-A Thorny Problem in Coal Utilization," Chemical Engineering, 87 (2), pp. 72-74 (1980).
21. Schlesinger, H. A., "Flue Gas Desulfurization Sludge Disposal Practices for Coal-Fired Steam and Power Plants," Mining Engineering (October, 1980), pp. 1516-1520.
22. Sastry, K. V. S., Editor, Agglomeration 77. Proceedings of the Second International Symposium on Agglomeration, Atlanta, Georgia, March 6-10, 1977, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc. New York, New York (1977).

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUS-
TRATIONS

3/8"

BEGIN
FIRST
LINE OF
TEXT
HERE

TYPING GUIDE SHEET

CENTER
OF PAGE

TOP OF
IMAGE
AREA

DROPPED
HEAD.
BEGIN
SECTIONS
HERE

REFERENCES
(Continued)

23. Burnett, T. A. and Anderson, K. D., "Technical Review and Economic Evaluation of Spray Dryer FGD Systems," Preliminary Draft Report to the U. S. Environmental Protection Agency by Tennessee Valley Authority Energy Design and Operations (August, 1980).
24. Guthrie, K. M., "Data and Techniques for Preliminary...Capital Cost Estimating," Chemical Engineering, 76 (7), pp. 114-133 (1969).
25. Weaver, J. B., "Cost and Profitability Estimation," in Chemical Engineers Handbook, R. H. Perry and C. H. Chilton, Editors, McGraw-Hill Book Co., New York, New York, pp. 25-1-25-47 (1973).
26. Dryden, C. E. and Furlow, R. H., Chemical Engineering Costs, The Ohio State University, Columbus, Ohio (1966).
27. Mulor, A. L., Mineral Processing Equipment Costs and Preliminary Capital Cost Estimations, The Canadian Institute of Mining and Metallurgy (1978).
28. Kuhl, R. J., "Construction and Production Cost Estimating," Journal of Metals, 24 (7), pp. 39-44 (1972).
29. Samuel, E. A. and Lapp, D. E., Testing and Assessment of a Baghouse for Dry SO₂ Removal - Task 4: SO₂ Removal Using Dry Sodium Compounds, Draft Report from the Buell Emission Control Division of Envirotech Corporation to the U. S. Environmental Protection Agency (September, 1980) under Contract No. 68-02-3119.

BEGIN
LAST LINE
OF TEXT

BOTTOM OF
IMAGE AREA.
OUTSIDE
DIMENSION
FOR TABLES
AND ILLUSTRATIONS